



Calhoun: The NPS Institutional Archive
DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

An investigation into the effects of vermiculite
on NO_x reduction and additives on sooting
and exhaust infrared signature from a gas
turbine combustor

Engel, Kurt R.

Monterey, California. Naval Postgraduate School

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

<http://www.nps.edu/library>

NAVAL POSTGRADUATE SCHOOL Monterey, California



THESIS

AN INVESTIGATION INTO THE EFFECTS OF
VERMICULITE ON NO_x REDUCTION AND
ADDITIVES ON SOOTING AND EXHAUST
INFRARED SIGNATURE FROM A GAS
TURBINE COMBUSTOR

by

Kurt Richard Engel

September, 1990

Thesis Advisor:

David W. Netzer

Approved for public release; distribution is unlimited.

Thesis
E 44615

C-2

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93945-5002

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b. OFFICE SYMBOL (If applicable) Code AA	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
6c. ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000			7b. ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)					
10. SOURCE OF FUNDING NUMBERS					
PROGRAM ELEMENT NO		PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.	
11. TITLE (Include Security Classification) An Investigation Into the Effects of Vermiculite on NO _x Reduction and Additives on Sooting and Exhaust Infrared Signature from a Gas Turbine Exhaust					
12. PERSONAL AUTHOR(S) Engel, Kurt R.					
13a. TYPE OF REPORT Master's Thesis		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) September 1990	
15. PAGE COUNT 80					
16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or U.S. Government					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) NO _x Control; Gas Turbine Combustors; Gas Turbine Fuel Additives; Soot Control; Pollution Control		
FIELD	GROUP	SUB-GROUP			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) An experimental investigation was conducted to determine the feasibility of using catalytic reduction of NO _x emissions from a typical jet engine combustor in the test cell environment. A modified T-63 combustor in combination with an instrumented 21 foot augmentation tube containing a vermiculite catalyst was used. Several methods for containing the vermiculite were attempted. Both vermiculite and vermiculite which had been coated with thiourea were used. Up to 19% reduction in NO _x concentrations was obtained using the vermiculite coated with thiourea, however the pressure loss across the catalyst bed was measured to be 36 in. H ₂ O. The techniques used proved ineffective and unacceptable for gas turbine engine test cell applications. Tests were conducted using both Wynn's 15/590 and Catane TM (ferrocene) fuel supplements in order to determine their effectiveness for soot reduction and whether or not the exhaust plume could be changed. For the test					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Prof. David W. Netzer			22b. TELEPHONE (Include Area Code) (408) 646-2980		22c. OFFICE SYMBOL Code AAnt

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

(19) Continued: conditions utilized, the Wynn's additive was not effective in reducing the opacity of the exhaust plume nor for reducing the exhaust plume temperature. The Catane TM reduced the opacity by 6.2%, but had no significant effect on the plume IR signature.

Approved for public release; distribution is unlimited.

An Investigation Into the Effects of
Vermiculite on NO_x Reduction and Additives
on Sooting and Exhaust Infrared Signature
from a Gas Turbine Combustor

by

Kurt R. Engel
Lieutenant Commander, United States Navy
B.S., U.S. Merchant Marine Academy

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN Aeronautical Engineering

from the

NAVAL POSTGRADUATE SCHOOL
September 1990

Author:

Kurt R. Engel

Approved by:

D.W. Netzer, Thesis Advisor

R.P. Shreeve, Second Reader

E.R. Wood, Chairman

Department of Aeronautics and Astronautics

ABSTRACT

An experimental investigation was conducted to determine the feasibility of using catalytic reduction of NO_x emissions from a typical jet engine combustor in the test cell environment. A modified T-63 combustor in combination with an instrumented 21 foot augmentation tube containing a vermiculite catalyst was used. Several methods for containing the vermiculite were attempted. Both vermiculite and vermiculite which had been coated with thiourea were used. Up to 19% reduction in NO_x concentrations was obtained using the vermiculite coated with thiourea, however the pressure loss across the catalyst bed was measured to be 36 in. H₂O. The techniques used proved ineffective and unacceptable for gas turbine engine test cell applications. Tests were conducted using both Wynn's W-15\590 and Catane TM (ferrocene) fuel supplements in order to determine their effectiveness for soot reduction and whether or not the exhaust plume could be changed. For the test conditions utilized, the Wynn's additive was not effective in reducing the opacity of the exhaust plume, nor for reducing the exhaust plume temperature. The Catane TM reduced the opacity by 6.2%, but also had no significant effect on the plume IR signature.

TABLE OF CONTENTS

I.	INTRODUCTION	1
II.	EXPERIMENTAL APPARATUS	7
	A. COMBUSTOR	7
	B. AIR SUPPLY	8
	C. FUEL SUPPLY	10
	D. TEMPERATURE AND PRESSURE RECORDING	11
	E. AUGMENTOR TUBE	12
	F. OPTICS	15
	G. INFRARED MEASUREMENT EQUIPMENT	16
	H. GAS ANALYSIS EQUIPMENT	18
	1. Model 900 Heated Sample Gas Dilution Unit	18
	2. Model 10AR NO/NOX Analyzer	18
	3. Model 48 CO Analyzer	20
	I. CONTROL ROOM	20
	J. DATA COLLECTION	21
III.	EXPERIMENTAL PROCEDURE	22
	A. NO _x REDUCTION STUDIES	22
	B. ADDITIVE STUDIES	24
IV.	RESULTS AND DISCUSSION	27

A. NO _x REDUCTION STUDIES	27
B. ADDITIVE STUDIES	29
1. Plume Opacity	30
2. Burner Efficiency	30
3. Infrared Signature Studies	31
V. CONCLUSIONS AND RECOMMENDATIONS	41
A. NO _x REDUCTION	41
B. ADDITIVE STUDIES	41
APPENDIX A	43
APPENDIX B	57
APPENDIX C	61
APPENDIX D	63
APPENDIX E	64
LIST OF REFERENCES	65
INITIAL DISTRIBUTION LIST	67

LIST OF TABLES

I.	T-63 OPERATING SPECIFICATIONS	8
II.	PROPERTIES OF FUELS	10
III.	DATA ACQUISITION CHANNEL KEY.	11
IV.	NO _x REDUCTION SUMMARY.	27
V.	EFFICIENCY RESULTS.	31
VI.	SUMMARY OF IR RESULTS.	38

LIST OF FIGURES

Figure 1 Emissions Characteristics of Gas Turbine Engines	2
Figure 2 Schematic of Air and Fuel Supply [Ref. 3] . .	9
Figure 3 Photograph of Augmentor Tube	13
Figure 4 Schematic of Augmentor Tube and Instrumentation	14
Figure 5 Determination of Augmentation Ratio	15
Figure 6 Photograph of Pitot-Static Traverse	16
Figure 7 Photograph of IR Scanner	17
Figure 8 Schematic of Sample Gas Flow	19
Figure 9 Photograph of Grades A-6 and Coarse Vermiculite and Perlite	25
Figure 10 Photograph of Laser and IR Measurement Equipment	26
Figure 11 Plume w/o Catane	33
Figure 12 Plume with Catane TM	34
Figure 13 Plume w/o 15/590	35
Figure 14 Plume with 15/590	36

NOMENCLATURE

AR	Augmentation Ratio
cm	Centimeters
CO	Carbon monoxide
CO ₂	Carbon dioxide
cSt	Centistokes
CH ₄	Methane
D	Diameter
DACU	Data acquisition and control unit
EPA	Environmental Protection Agency
f	Fuel to air ratio
F	Fahrenheit
GPM	Gallons per minute
HP	Hewlett-Packard
IBP	Initial boiling point
m	Mass flow rate
mV	Millivolts
NADEP	Naval Aviation Depot
NO	Nitric oxide
NO _x	Nitrogen oxides
NO ₂	Nitrous oxide
NPS	Naval Postgraduate School
N ₂	Nitrogen
O ₃	Ozone

p	Pressure
ppm	Parts per million
psi	Pounds per square inch
R	Rankine
SCFH	Standard cubic foot per hour
SCR	Selective Catalytic Reduction
SO _x	Sulfur oxides
T	Temperature
UHC	Unburned hydrocarbons
V	Velocity

Subscripts/Superscripts

a	Air
augup	Upstream of catalyst in augmentor tube
avg	Average value across tube
bp	Bypass
c	Combustor
ex1	Upstream of quench air in combustor
ex2	Downstream of quench air in combustor
t	Stagnation or total
*	Nozzle throat conditions

ACKNOWLEDGEMENTS

I would like to thank the technical staff of the Aeronautics and Astronautics for turning out quality work parts from my rough scratches on paper. I especially want to thank Pat Hickey, Don Harvey, John Moulton and Harry Conner.

A special thanks to my advisor, Professor Dave Netzer, "who always knew."

Last but not least, I want to thank my wife, Celia, who never had a doubt.

I. INTRODUCTION

Combustion-generated pollution of the environment from the operation of gas turbine engines comes in many forms. The large volumes of noxious gases and particulates generated by thousands of gas turbine engines worldwide can upset the environment if controls are not instituted.

The major sources of air pollution are listed below [Ref.1]:

- Soot or smoke from the carbon in the fuel that was unable to fully burn in the combustor.
- Unburned hydrocarbons (UHC) from incomplete combustion.
- Oxides of nitrogen (NO_x), a majority of which comes from nitrogen in the atmosphere in the presence of oxygen at high temperatures.
- Carbon monoxide (CO) resulting from incomplete combustion.
- Oxides of sulfur (SO_x) which come almost entirely from sulfur present in the fuel.

Soot or smoke is the most obvious pollutant and much effort has been made to control concentration and particulate size. CO and UHC levels are controlled when the engine is operated efficiently near stoichiometric limits. Unfortunately, as can be seen from Figure 1, this is also where the levels of smoke and NO_x increase [Ref.1].

Sulfur oxides are particularly damaging, not only to the environment but also to the engine. SO_x combines in the atmosphere to form sulfuric acid which is damaging to the environment and to internal engine parts. However, it is possible to remove the sulfur in the refining process and MILSPEC's require less than 0.1 % sulfur by mass in jet fuel to control the effects of sulfur. Because of these efforts SO_x pollution from gas turbines is minimal.

Soot size and concentration has been studied extensively at the Naval Postgraduate School [Refs. 2 and 3] and by Cashdollar [Ref. 4].

The Environmental Protection Agency has written goals for commercial engine manufacturers concerning emissions and these goals have been generally met.

Military engines are exempt from these requirements when operated on an aircraft. However, it has been determined that engines operated in a test cell are subject to the emissions regulations applicable to a stationary gas turbine power plant. A typical Naval Aviation Depot (NADEP) runs an engine

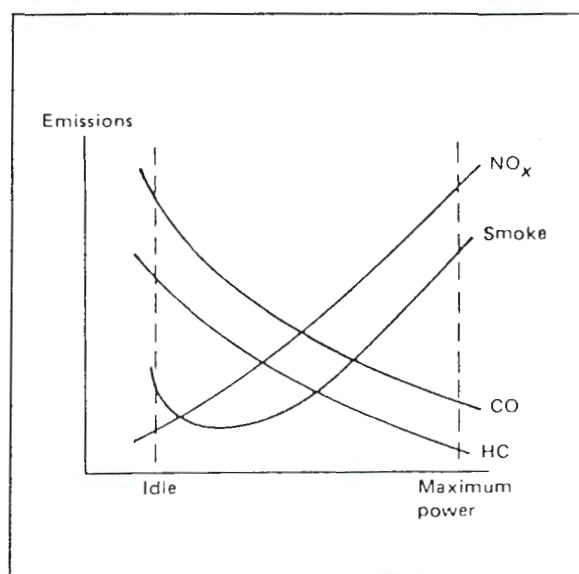


Figure 1 Emissions Characteristics of Gas Turbine Engines

for five to six hours before it is approved for use in an aircraft.

In Northern California, the Bay Area Air Quality Management District closely monitors emissions from fixed sources in its jurisdiction. NO_x emissions are limited to 150 lbs/day for existing sources and new sources are limited to 10 ppm. Sooting limits are any concentration exceeding one on the Ringleman scale for greater than 30 minutes. There is a wide variety of additives available on the market. At this time the U.S. Navy at NADEP Alameda uses Cerium Hex Cem soot suppressing additive when testing the T-56 engine. At the United Airlines test cells at San Francisco International Airport, DTG-2, a barium based chemical, is used to control the sooting of turbojet engines. These metal based additives are usually effective in controlling the soot but there are draw backs:

- They tend to form deposits in the engines, consequently their use is time limited.
- They are aggressive chemicals that can cause damage to the seals in the engine.
- Some additives (in particular barium and manganese based) are toxic and may have long term effects worse than the soot itself. [Ref. 1 and 5]

For these reasons it is hoped that an inexpensive additive can be found that does not contain metal and will reduce sooting. Wynn's W-15/590 claims to be one such product. In addition to soot reduction, the additives can

increase the combustion efficiency in some types of engines. The effects of these additives on the exhaust IR signature is unknown.

NO_x is produced to a certain extent in all combustion that reaches at least 3200 R. It is largely independent of the fuel and solely dependent on the flame temperature in the primary zone. The production is by the following reactions at a very fast rate [Ref. 6]:



and



The source of the nitrogen is the atmosphere and can not be controlled. Therefore, the only way to reduce the NO_x is to change the combustion temperature with staged burning or water injection [Ref. 6], or treat the entire exhaust flow with a scrubber or absorber system [Ref. 7].

A scrubber system would not be the best choice for a treatment system because of the complexity of required plumbing. It was discovered in a U.S. Air Force funded study that in laboratory conditions it is possible to remove up to 96% of the NO_x from a combustion stream using the catalytic and adsorbing properties of vermiculite [Ref. 8].

Vermiculite is an inexpensive silicate with the formula $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot x\text{H}_2\text{O}$. It is related to mica and talc and has

the unique property of expanding upon heating up to 30 times original volume. It is non-toxic and frequently used in potting soil and as an insulator in the building industry [Ref. 9]. Its catalytic properties are not well understood.

Catalytic reduction of NO_x is a much studied problem in industry. Typically commercial Selective Catalyst Reduction (SCR) beds are constructed of precious metals or natural and manmade zeolites. Mobil Oil Corp. makes one such catalyst ZSM-5 [Ref. 10]. These SCR's require ammonia injection in the ratio of one-to-one on a molal basis with NO_x . When combined with combustion chamber water injection these SCR beds are able to achieve 85% reduction in exhaust flow NO_x concentration.

While this installation works well for steady state commercial operations, it is not believed the precise control of ammonia injection would be possible with the rapid throttle movements necessary in engine test. If too little ammonia is injected the NO_x is not reduced and if too much ammonia is injected it passes through the SCR unused and is called "slip". In addition, the efficiency of the reduction of NO_x with ammonia in a SCR is very temperature dependent. Typically the SCR bed must be maintained at a constant 700 deg. F.

The following goals were set as achievable within the time available for the present investigation:

- Acquire vermiculite catalyst and chemicals that seemed likely to produce the best results in typical engine test cells.
- Redesign the catalyst containment to eliminate the large pressure drop associated with the existing design.
- Measure the effectiveness of various catalyst bed depths and chemical coatings on reduction of NO_x and CO.
- Compare the effectiveness of Wynn's W-15/590 additive to Catane TM (ferrocene) for soot emission reduction.
- Evaluate the effects of W-15/590 and Catane TM (ferrocene) on the exhaust plume thermal distribution.

II. EXPERIMENTAL APPARATUS

A. COMBUSTOR

The production of combustion gases was accomplished using an Allison T-63-A-5A gas turbine combustion chamber as modified by Grafton [Ref. 11]. The modifications included the addition of a quench manifold to simulate the temperature drop resulting from work extraction of the gas producer turbine and the power turbine. In contrast to Behrens [Ref. 12] investigation, during the NO_x portion of this research the quench was not used. This was done to prolong the high temperatures of the primary zone and boost the production of NO_x .

The quench was used in the soot studies to help quench the soot formed, and prevent its combustion. The quench air was supplied from the main air line through a sonic choke ($D_{bp} = 0.242$ in.) sized to provide 0.5 lbm/sec flow with a minimum pressure of 475 psi from the main air line.

Prior to initial runs all connections were checked for security, and filters and ignitors were cleaned. Optical windows were cleaned prior to each run. A gas bottle of nitrogen was connected to a portion of the existing purge piping to flow across the windows and ensure they did not

obscure with soot. Table I is a list of operating parameters for the T-63 at sea level standard conditions.

TABLE I T-63 OPERATING SPECIFICATIONS [Ref. 13]

Rating	f	$\dot{m}_{air}$	$\dot{m}_{fuel}$	T_t
		lb/sec	lb/sec	deg F
Takeoff	0.019	3.17	0.061	1380
Military	0.017	3.04	0.053	1280
90%	0.017	2.95	0.049	1226
75%	0.015	2.82	0.043	1148

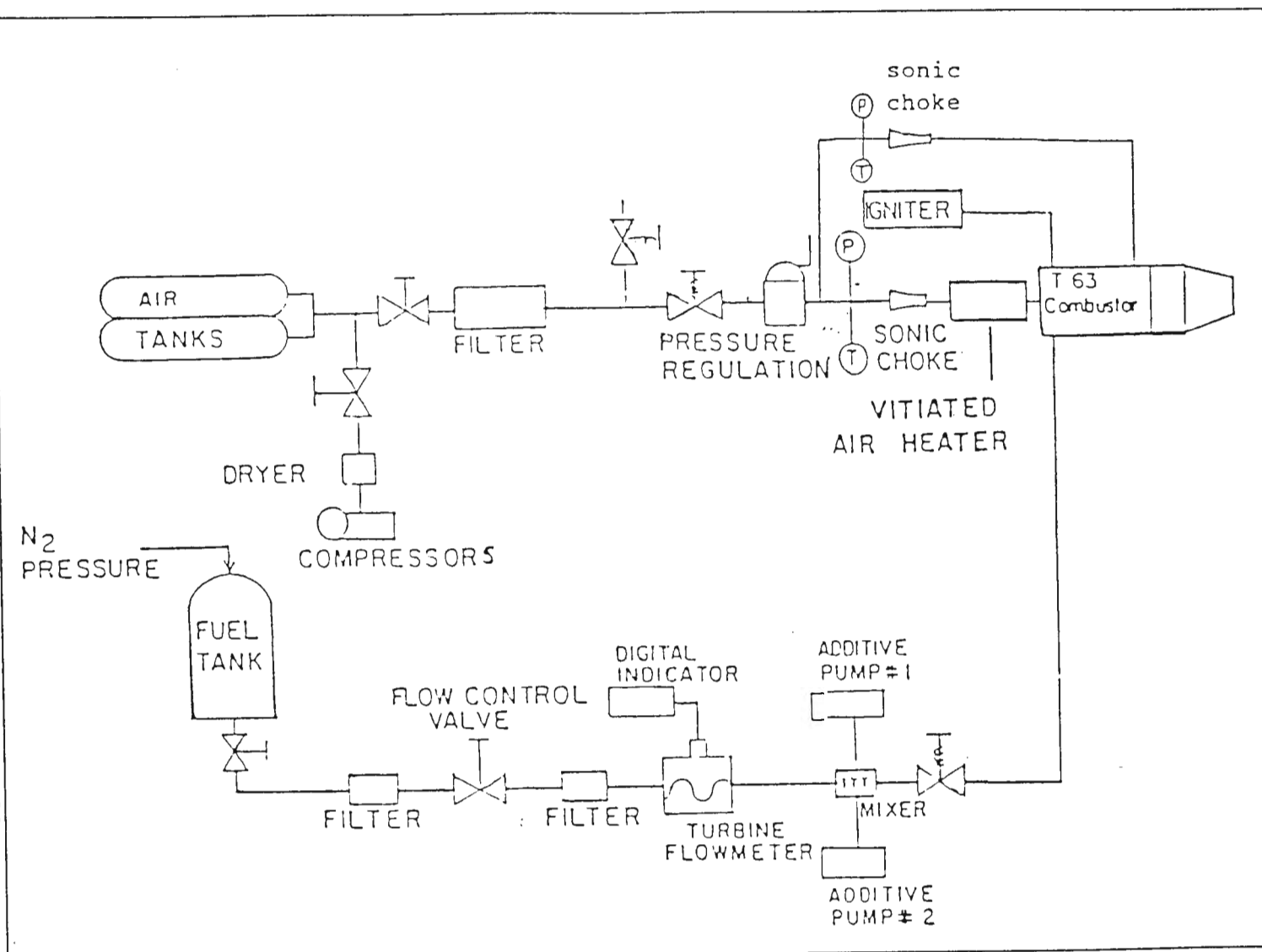
Note: compressor pressure ratio= 6.25, P_c =92 psi,
engine length= 40.4 in, width= 19.0 in, weight= 138.7 lbs.
height= 22.5 in. Military power limited to 30 min.

B. AIR SUPPLY

Compressed air to run the combustion chamber was supplied by a bank of air tanks pressurized to 3000 PSI (Figure 2). These tanks were filled between runs by compressors with an air dryer. The air supply could operate the T-63 combustor at the Military power level for approximately 7 minutes.

A pneumatically powered, dome loaded pressure regulator was operated from the control room to regulate the air pressure through the sonic chokes. The temperatures and pressures were read by the HP computer system and used to

Figure 2 Schematic of Air and Fuel Supply [Ref. 3]



compute the air mass flow rate.

C. FUEL SUPPLY

Metered fuel was supplied to the combustion chamber through the fuel atomizer in the top of the chamber (Figure 2). The 20 gallon fuel tank was pressurized with nitrogen and the flow rate was controlled using a throttle valve in the control room. The turbine flowmeter signal, in gallons per minute (GPM), was read in the control room at a digital display and also recorded by the data acquisition system. The properties of the fuels employed are listed in Table II. The fuel additives were injected into the fuel line in a mixing chamber at the specified concentration via two Eldex additive pumps. These pumps were operated from the control room and allowed isolation of the effects of the additive.

TABLE II PROPERTIES OF FUELS [Ref. 3]

Properties of Fuel	NAPC 3	NAPC 4
API Gravity @ 15 deg C	41.3	41.6
Distillation IBP deg C	171	180
Temperature recovered 10% deg C	192	202
Temperature recovered 20% deg C	203	210
Temperature recovered 50% deg C	227	228
Temperature recovered 90% deg C	261	264
End Point deg C	276	282
Residue ml	1.4	1.4
Loss ml	0.1	0.5
Composition Aromatics vol%, max	22.8	18.6

Properties of Fuel	NAPC 3	NAPC 4
Olefins vol%	0.75	0.79
Hydrogen content wt%	13.66	13.82
Smoke Point mm	20.0	21.0
Aniline-Gravity Prod.	5811	6140
Freeze Point	-34.0	-34.5
Temperature @ 12 cSt deg C	-35.6	-31.7
Viscosity @ 37.8 deg C cSt	1.62	1.74

D. TEMPERATURE AND PRESSURE RECORDING

Nine thermocouples and four pressure transducers were read by the Hewlett-Packard (HP) 3054A Data Acquisition/Control Unit (DACU). The computer read the data and made calculations for output during hot runs. All thermocouples were Chromel-Alumel (Type K) and the computer was programmed to convert analog readings to temperatures for printout. Table III provides the acquisition channel numbers and parameters measured:

TABLE III DATA ACQUISITION CHANNEL KEY

Parameter	DACU Chan No.
P_a main air pressure	24
P_c combustion chamber pressure	23
P_{hf} heater fuel pressure	22
P_{ho} heater make up oxygen	21
T_a main air temperature	60

Parameter	DACU Chan No.
T_{cin} combustor air inlet	61
T_{ex1} combustor exhaust upstream quench	62
T_{ex2} combustor exhaust downstream quench	63
T_{ho} heater make-up oxygen	64
T_{hf} heater fuel temperature	65
T_{augup} augmentor temp upstream	66
T_{augd1} augmentor temp downstream	67
T_{augd2} augmentor temp downstream	68

E. AUGMENTOR TUBE

The steel augmentor tube as described by Behrens [Ref. 12] was used for preliminary runs. It was then modified to the configuration shown in Figures 3 and 4. The vertical portion of the augmentor tube was divided with stainless steel mesh into different bed screen spacings and partially filled with vermiculite. This method was chosen to eliminate to the maximum extent possible the pressure loss due to the vermiculite in the exhaust flow. The catalyst basket used by Behrens [Ref. 12] was split in half and formed the top and bottom of a variable distance fluidized bed in the exhaust flow for the vermiculite. Inside the augmentor tube a deflector plate was installed at 45 deg. at the tube bend to

help turn the flow. The deflector plate was sized so that it did not restrict the tube cross section.

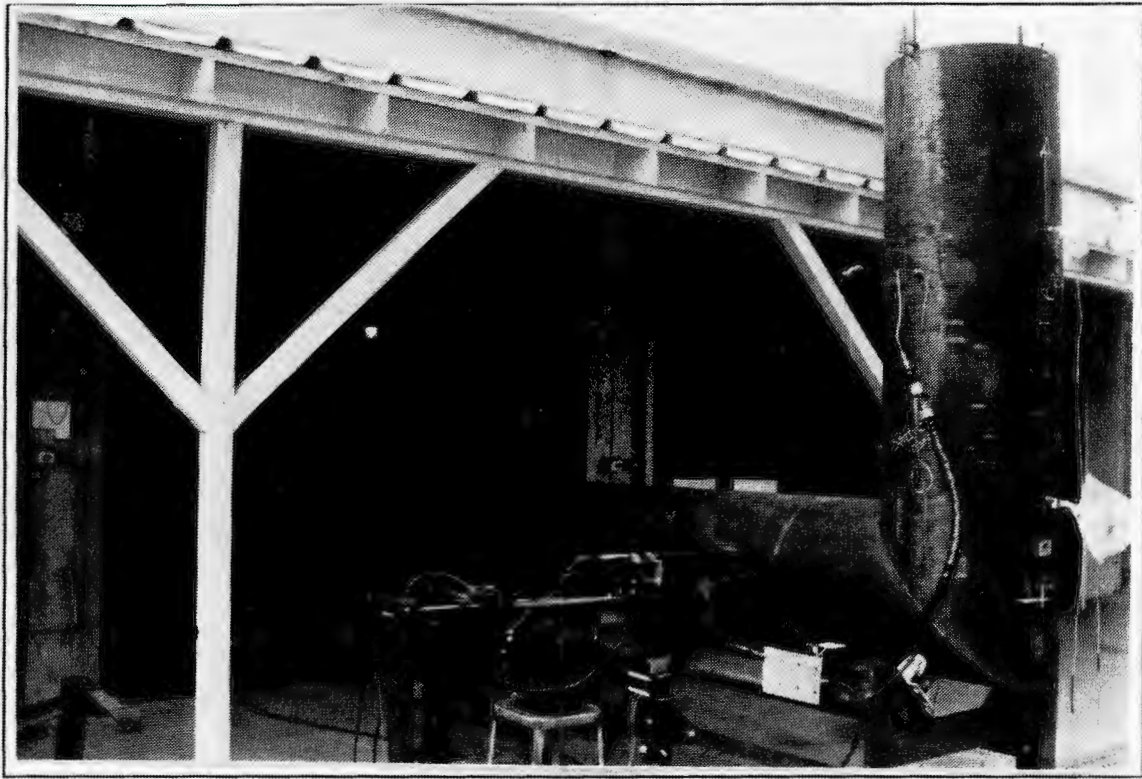


Figure 3 Photograph of Augmentor Tube

A blocking plate was attached to the front of the augmentor tube. The opening of the plate could be adjusted to regulate the amount of augmentation air entrained with the engine exhaust, and thereby change the augmentation ratio (Figure 5). In these experiments the five inch diameter opening was not varied.

Determination of the total mass flow through the augmentor tube was made by measuring the velocity profile and gas temperature. A motor driven traversing pitot-static system (Figure 6) was mounted 24 inches upstream of the turning

baffle. A slant tube manometer was used to record $P_t - P$ across the tube diameter.

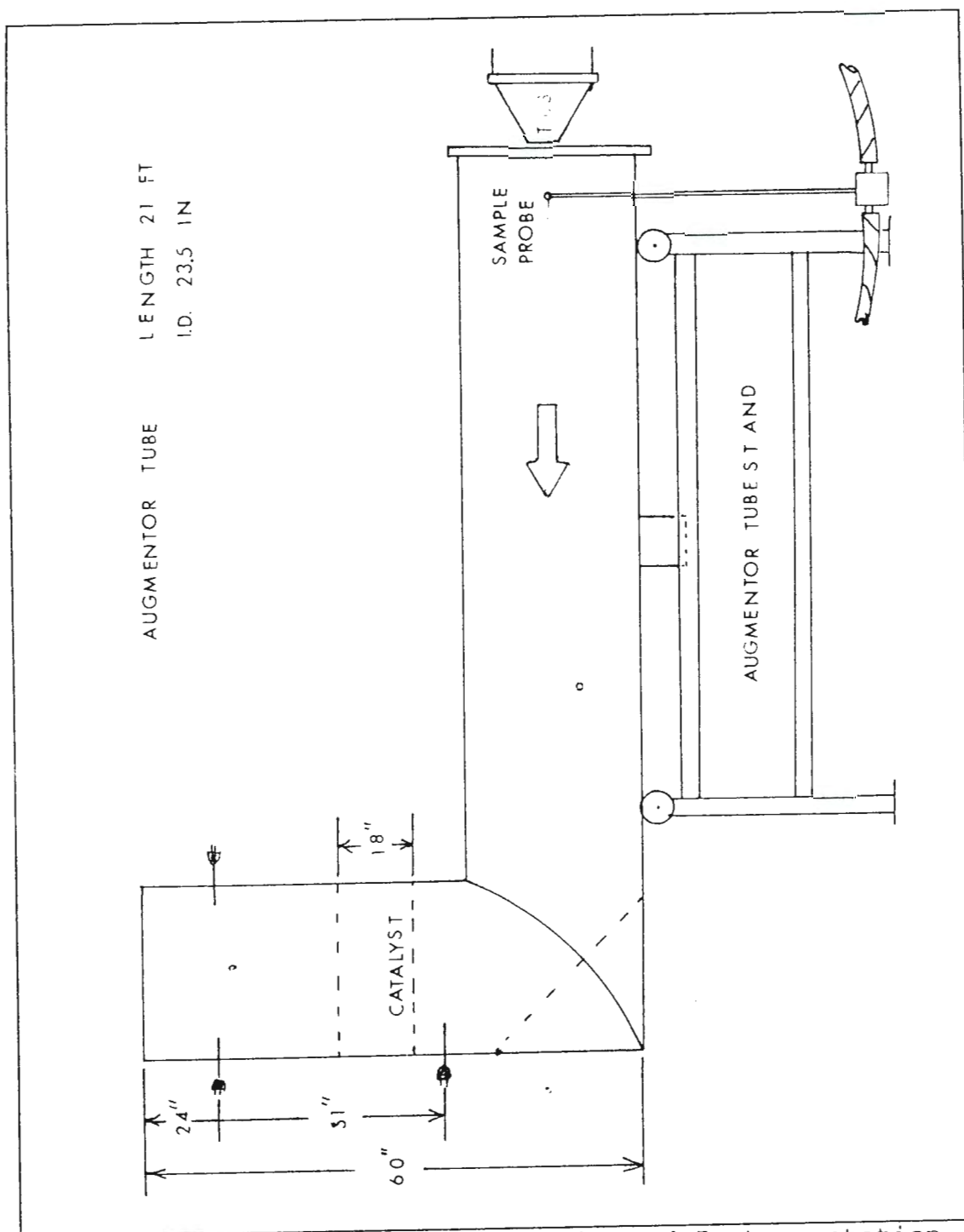


Figure 4 Schematic of Augmentor Tube and Instrumentation

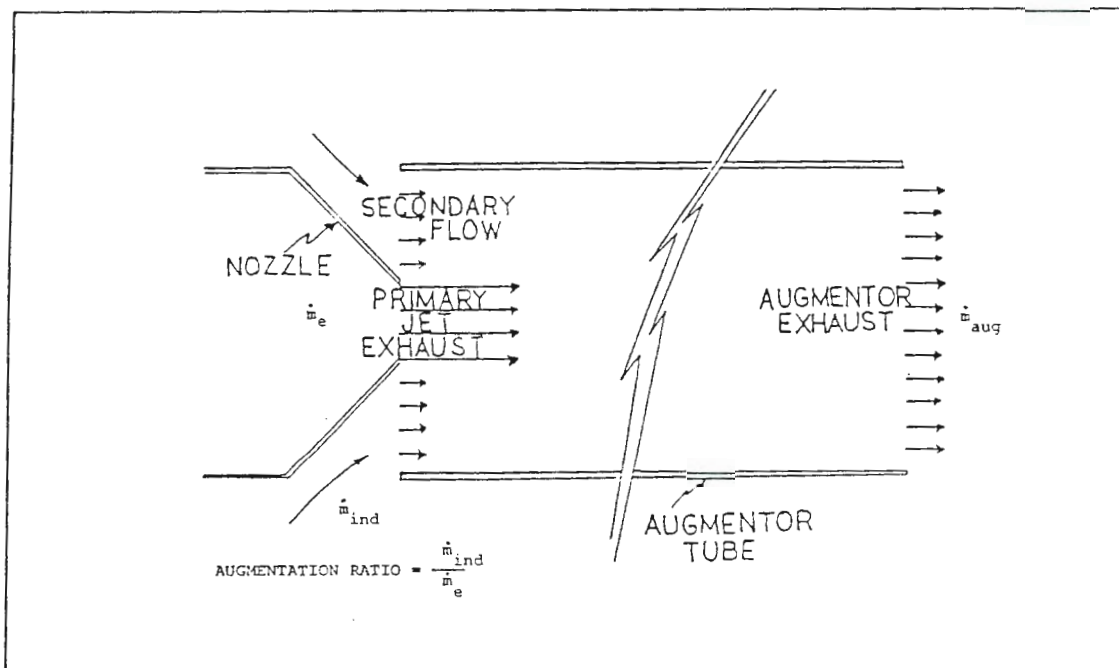


Figure 5 Determination of Augmentation Ratio

F. OPTICS

The transmittance measurements were made with a single laser through the combustion chamber to a photodiode target. Transmittance was measured at several locations through the exhaust stream. It was decided to use the forward most optical ports with purge tubing in the aft combustor can since it offered the most observable transmittance measurements. The diode output signal was amplified and recorded on a strip chart recorder in the control room. The source was a 0.6328 micron helium-neon laser operating at 8mW. A 50% narrow band pass filter was used to reduce the adverse effects of ambient light.

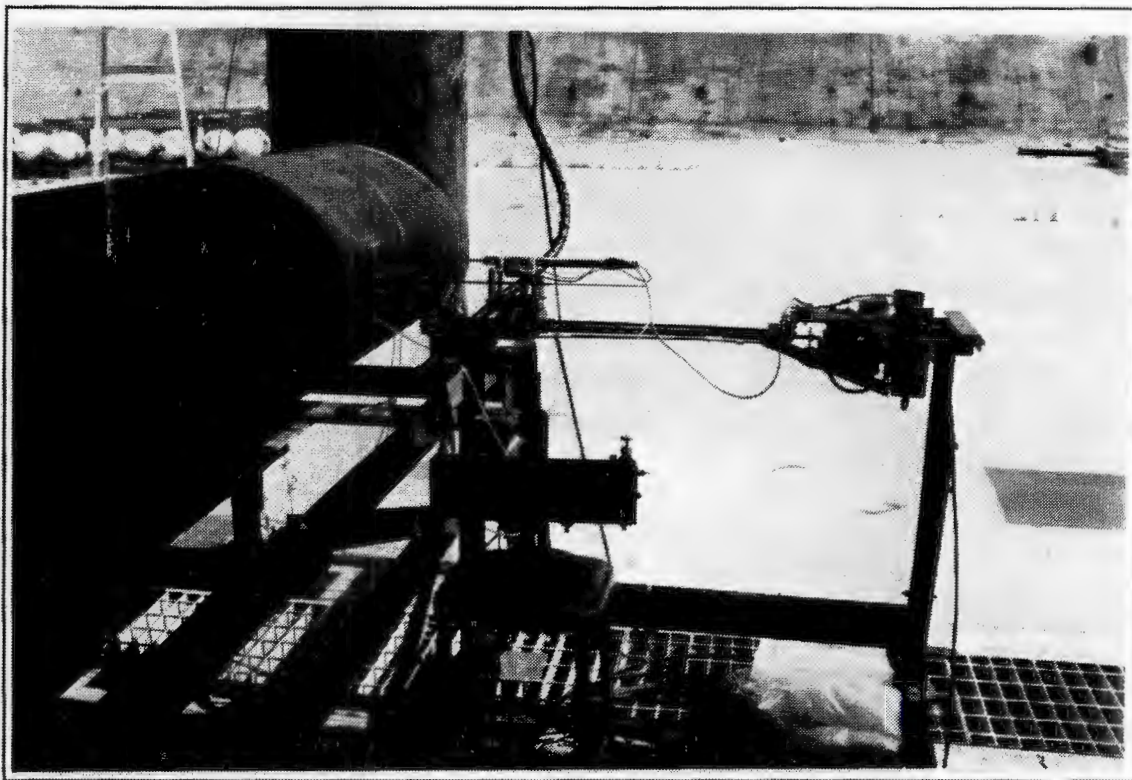


Figure 6 Photograph of Pitot-Static Traverse

G. INFRARED MEASUREMENT EQUIPMENT

Infrared measurements of the gas temperatures were made using an Agema real time thermal imaging system. The scanner was equipped with a 20 deg field of view lens and three filter settings for use in different thermal ranges (Figure 7). The surface of the object was scanned 25 times per second, producing a TV-like image. The detector was thermoelectrically cooled and a built-in black body source provided a reference for self calibration. The scanner operated in the short wavelength band (SWB) of the middle IR spectrum between two and 5.6 microns wavelength. The picture produced had 280 lines per frame with 100 elements/line. Temperature accuracy

was better than $\pm 2^{\circ} \text{C}$. The Noise Equivalent Temperature Difference was 0.1°C at 30°C .



Figure 7 Photograph of IR Scanner

Scanner images were processed by a dedicated Compaq 286 PC with CATS E software and hardware. The software gave the standard 40 Mb hard disk the capability to store 930 IR images. These images could be either single shots, rapid sequences or integrations over a period of time. The software offered many features for post run analysis. These included: subtraction of one image from another, magnification, relief, and an auto scaling feature. Complicated keystroke sequences could be stored in macro programs to be run during the short test runs. Correct temperature display required knowledge of

the emissivity of the object viewed. The CATS E software offered calculation of the emissivity of complex emissivity distribution scenes.

H. GAS ANALYSIS EQUIPMENT

Gas samples were taken both upstream and downstream of the catalyst to determine its effectiveness. The upstream sample was taken from the center of the augmentor tube eight inches downstream from the opening. This location precluded any ambient air from diluting the sample. The downstream sample location was taken 12 inches above the top catalyst screen. A three-way solenoid valve operated from the control room allowed choice of sample location.

The sample line heater mentioned in Behrens [Ref. 12] malfunctioned during early runs. It was determined by testing that the NO_x readings were not affected.

1. Model 900 Heated Sample Gas Dilution Unit

Sample gas was drawn by vacuum pumps into the Thermo Environmental Model 900 at 1.3 SCFH, and mixed with dilution air at a 20:1 ratio. The sample was heated and filtered and then sent to the Model 10AR and Model 48 [Ref. 14]. Figure 8 is a schematic for the sample flow path.

2. Model 10AR NO/NOX Analyzer

The conditioned and diluted sample was fed through teflon tubing to the Thermo Environmental Model 10AR NO/NO_x Gas Analyzer. The Model 10AR was capable of continuous

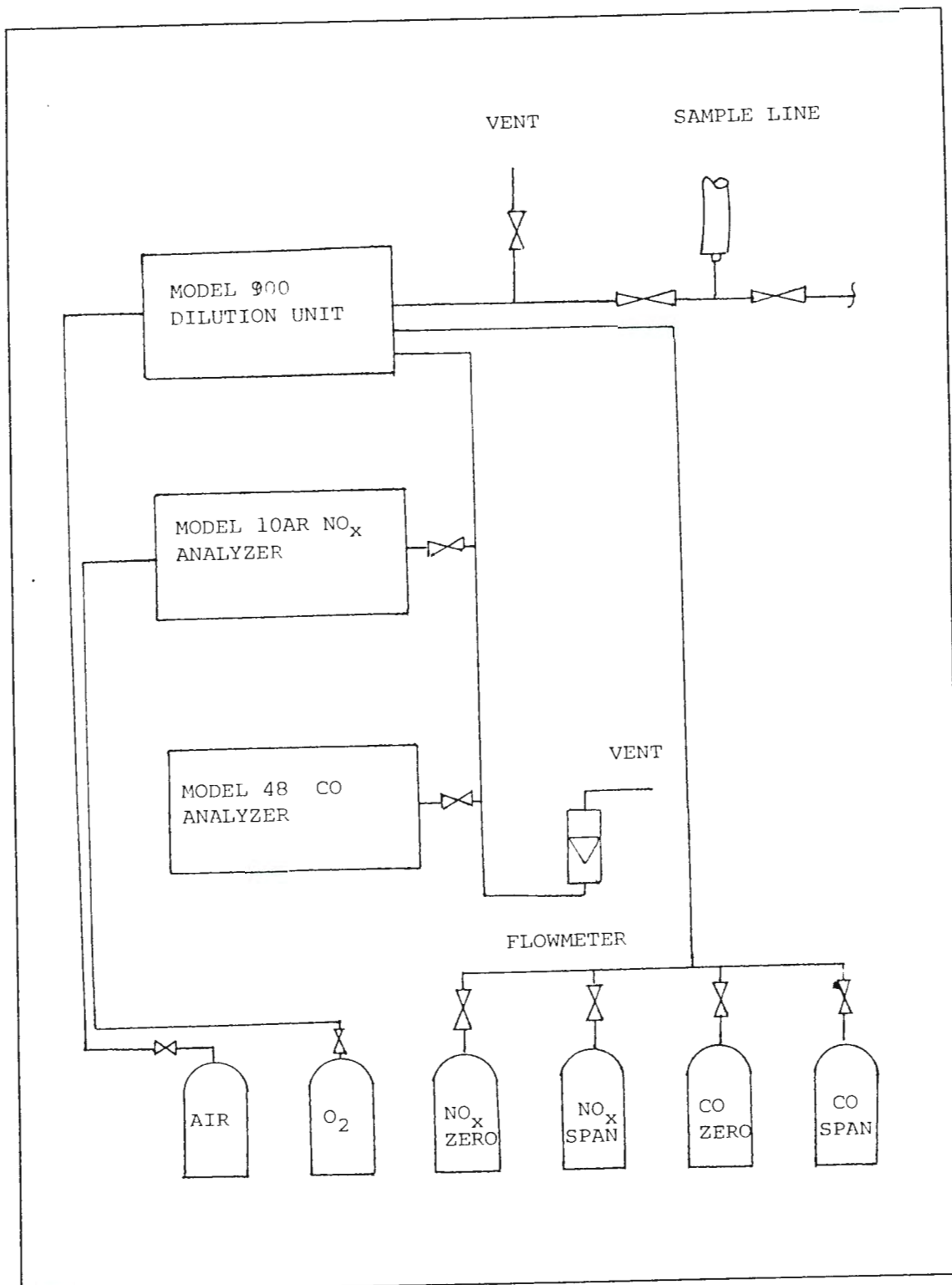


Figure 8 Schematic of Sample Gas Flow

readings of nitric oxide (NO) or a mix of oxides of nitrogen (NO + NO_x or NO_x). The analyzer read in ranges from 2.5 to 10,000 parts-per-million (ppm) and had a sensitivity of .1 ppm. All readings were corrected for the dilution ratio to get the true raw sample concentration.

The operating principle for this analyzer is the chemiluminescent reaction of NO and ozone (O₃), namely



The analyzer first converted all the sample gas NO_x to NO through a thermal NO₂-to-NO converter. Then the analyzer mixed the NO with ozone from an internal generator. The resulting chemiluminescence was measured on a photomultiplier (PM) and was read on the dial. The output of the PM was linearly proportional to the NO concentration [Ref. 15].

3. Model 48 CO Analyzer

A portion of the output from the Model 900 went to the Model 48 CO Analyzer. This analysis was made using non-dispersive infrared absorption techniques. While the output was non-linear, it was linearized using stored calibration curves from computer memory [Ref. 16]. The analyzer was accurate to 0.1 ppm and read from 0.1 to 1000 ppm. Like the Model 10AR, readings were multiplied by 20, the dilution ratio, to get the raw sample concentration.

I. CONTROL ROOM

The control room was located adjacent to the test cell with the T-63 combustor and had two windows for viewing the tests. All controls for operating the fuel, air, additive pumps, and gas sampling equipment were located there. The only changes made since Behrens investigation [Ref. 12] was moving all calibration and zero gases outside the control room and plumbing them to the analyzers.

J. DATA COLLECTION

Data acquisition and reduction was accomplished by the Hewlett-Packard HP-3054A automatic data acquisition/control system located in the control room. The test data was controlled by a program (Appendix A) written in HP Basic 5.1. The program was stored on the hard disk and included subroutines for calibration of transducers, set up of gas flows, and reduction of hot run data. Transmittance data and gas concentrations were taken directly from the strip chart recorder and analyzers respectively.

III. EXPERIMENTAL PROCEDURE

Calibration of all equipment was standard operating procedure before all data runs. A checklist (Appendix B) was used to ensure no critical items were forgotten. Appendix C was developed to ensure the gas analyzers were reading accurately.

A. NO_x REDUCTION STUDIES

For NO_x studies, the gas analyzers were calibrated with zero and span gases in accordance with References 14-16. The Model 10AR required a zero gas of less than 0.1 ppm NO_x and a span gas with 220 ppm NO in nitrogen. The Model 48 was calibrated with a zero gas containing less than 0.1 ppm CO and a span gas with 104 ppm CO in air. Since both analyzers received sample air which had been filtered and diluted at a 20:1 ratio, the meter reading required a factor of 20 to get the raw sample concentration in ppm.

The program "T63NOX" (Appendix A) was written in HP BASIC and used to collect data. It contained a calibration routine which was used prior to data runs to calibrate the pressure transducers. With known pressures on the transducers, new calibration constants were calculated and entered into the program for data reduction.

The augmentor tube velocities were calculated using a Kiel probe measurement of total pressure and a wall port measurement, at the same station. A slant tube manometer read the difference. A built-in level was used to assure accurate readings to within 0.01 inches of H₂O. Probe position was measured with a linear variable differential transformer (LVDT) and output to a strip chart recorder in the control room. Catalyst bed pressure loss was measured with a U-tube manometer filled with dyed water. To allow safe remote readings, a video camera relayed both manometer readings to a monitor in the control room.

After completing the run checklist (Appendix B), gas analyzer checklist (Appendix C), and all equipment was set for a run, the combustor was ignited. The combustor was operated in accordance with Table I at fuel to air ratios of $f = 0.017-0.019$. Once a steady operating condition was reached, the data acquisition program was activated and the conditions were not changed for the duration of the run. The Kiel probe was traversed across the augmentor tube and the pressure readings recorded.

Run times were usually five to six minutes. The gas sampling was started upstream of the bed and lasted long enough for the NO_x and CO concentrations to stabilize. This typically took two or three minutes. The downstream sample was then taken for the balance of the run. When the concentrations stabilized, the readings were taken.

It was desired to conduct several runs using vermiculite coated with different chemicals which had been successful for Nelson [Reference 8]. The coating process for the vermiculite involved wetting the vermiculite with water and then mixing in thiourea. The thiourea was mixed 20% by weight. After thorough mixing, the vermiculite was spread in pans and baked overnight at 120° C.

Vermiculite is available in several grades. A-6 (extra coarse) is the largest with an average size of 3/8 in. Coarse averages 1/4 in (Figure 9). A method to reduce pressure loss of the bed discovered by Behrens, was to use larger size catalyst. While it had been reported [Reference 8] that A-6 grade was not as effective at NO_x reduction as the coarse grade, it was felt that the larger size would offer the least pressure loss. A-6 grade was the largest grade available and is more difficult to acquire. Extra coarse perlite (sodium-potassium-aluminum-silicate), as evaluated by Behrens, was unavailable.

B. ADDITIVE STUDIES

During the additive studies, prior to each run the Eldex additive pumping rates were set against a back pressure of 100 psi to simulate the fuel pressure in the line in the mixing chamber. The pumping rates for the pumps were measured using a graduated cylinder over a known time. As a final check of additive pump rate, the level of the reservoirs were measured

before and after each run and the rate was calculated from the time of pump operation. The additive pumps were controlled from the control room.



Figure 9 Photograph of Grades A-6 and Coarse Vermiculite and Perlite

The laser was used to measure changes in transmittance during the additive studies. It was securely mounted and aimed through the forward window in the aft combustor can at the photodiode target (Figure 10). The alignment of the photodiode was adjusted for maximum power out and read on a strip chart in the control room. Prior to setting air flow rates or engine operation the window purge was turned on to prevent and loose soot from lodging on the windows.

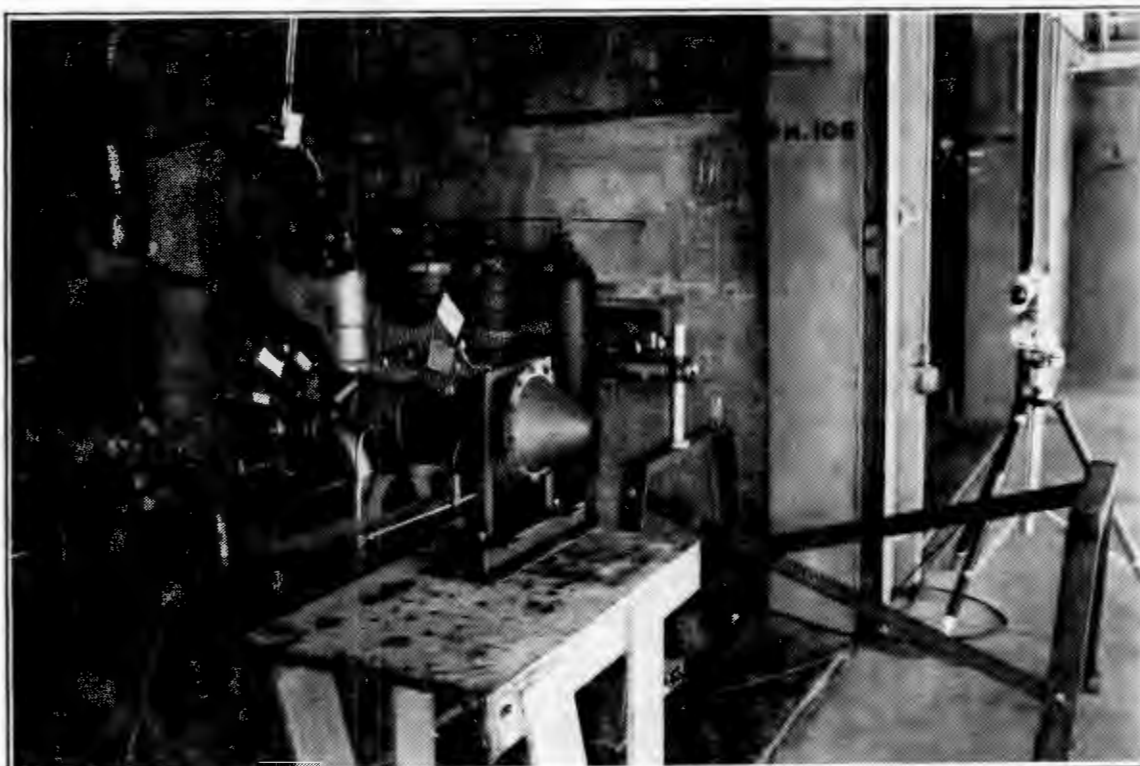


Figure 10 Photograph of Laser and IR Measurement Equipment

To measure the effects of the additives on the thermal signature of the T-63, the IR scanner was positioned in the test cell and aimed at the exhaust plume. For these runs the augmentor tube was rolled back out of the way to allow the plume to fully develop.

The CATS-E software with the IR system was programmed to average ten images three times during each run condition. At the same time the HP DACU was run with an abridged version of "T63NOX" to record P_c , T_{ex1} , and T_{ex2} . Appendix E was used for guidance during the short run period.

IV. RESULTS AND DISCUSSION

A. NO_x REDUCTION STUDIES

Shown in Table II is a synopsis of the NO_x reduction runs using vermiculite. Appendix D contains the computer output for each data run. NAPC 4 was used for all runs.

TABLE IV NO_x REDUCTION SUMMARY

Parameter	Run 1	Run 2	Run 3
catalyst used	Vermiculite A-6 coated with 20% wt thiourea	Vermiculite coated with 20% wt thiourea	Plain vermiculite 50-50 mix A-6 and coarse
bed depth (in.)	6	6	16
bed screen spacing (in.)	16	18	41
space velocity	185,760 hr ⁻¹	95,000 hr ⁻¹	43,000 hr ⁻¹
m _a (lbm/sec)	2.29	2.21	2.19
f	0.019	0.018	0.019
V _{avg} (ft/sec)	25.7	13.2	15.8
press. loss (in. H ₂ O)	34	36	32
AR	0.5	no AR, mass lost	no AR, mass lost
T _{augup} (deg. R)	904	991	998
T _{ex1} (deg. R)	1685	1700	1731

Parameter	Run 1	Run 2	Run 3
CO (ppm) up/down	832/470	1340/920	1117/856
NO _x (ppm) up/down	17/14	52/42	38/34
NO _x % reduction	17.6%	19%	11%

Notes: Run 1-Screen failed during run. NO_x reduction not sustained.

Runs 2 & 3-Augmentation less than 0. Mass flow lost out the front of the tube.

There were three major problems with the use of vermiculite in the test cell for NO_x reduction:

- It did not reduce the NO_x enough in the present installation to make it practicable.
- The flow resistance as presently configured was 36 in H₂O and far in excess of that permitted in a test cell.
- The cost of the chemical for adding ammonia (thiourea) is probably too expensive for economic use.

In the USAF funded study [Ref. 8] the space velocities (defined as bed volumes/unit time) ranged from 5,000 to 60,000 hr⁻¹. This gave the NO_x molecules a much longer time to react on the vermiculite. It would be possible to reduce the space velocity, but it would require extensive modifications to existing test cells.

The pressure loss through the bed is possibly the most important problem. Engines in the test cell are very sensitive to back pressure, and a resistance of as little as

From Table V it can be seen from the essentially unchanged values of k with either additive, that there was no increase in efficiency as defined by measured P_t and T_t .

3. Infrared Signature Studies

The exhaust plume thermal distributions obtained for the four conditions shown in Table VI are presented in Figures 11-14. It was observed that the temperature at the nozzle exhaust ($M=1$) had maximum values of approximately 233°C . This would imply nozzle inlet stagnation temperatures of approximately 275°C .

$$\dot{m} = C_D \frac{P_c A_{th}}{\sqrt{R T_t}} \sqrt{\gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}$$

becomes for a given engine in which γ and R are essentially constant,

$$\dot{m} = \frac{k P_c}{\sqrt{T_t}}$$

In the present tests, P_c and T_t were measured at the entrance to the exhaust nozzle (P_c and T_{ex1}).

The data for a test conditions were averaged and k was calculated. This was done for all conditions and the k values compared. Table V summarizes the result.

TABLE V EFFICIENCY RESULTS

Condition	$\dot{m}$ (lbm/sec)	T_{ex1} °R	P_c (psi) measured	k calculated
w/o Catane	1.94	1625	98.9	1.265
w Catane	1.925	1586	97.0	1.265
w/o 15/590	1.922	1582	97.9	1.281
w 15/590	1.905	1595	97.5	1.281

1. Plume Opacity

Data were taken in accordance with Appendix E. Transmittance output is shown in Appendix D. For both additives, 100% transmittance was taken after the fuel was shut off, but while the purge and main air flows were on.

The Wynn's additive 15/590 had no effect on the transmittance through the combustor of the T-63 when used at the recommended rate of 22.5 ml/gal, or 0.6% by volume.

The Catane TM (ferrocene) has been studied previously in the present lab and has proven effective in reducing the mass concentration of the soot. In the present installation, using NAPC 3 fuel, the Catane TM reduced the sooting by 6.2% when used at the rate of 26.5 ml/gal.

2. Burner Efficiency

It was realized that burner efficiency is very high in most gas turbine combustors operating at high pressure. However, liquid fueled ramjets do not operate at such high pressures or combustion efficiencies. The T-63 operates at typical ramjet pressure. There was some question that with a reduction in soot there might be some increase in the heat released. Further, the Wynn's Co. had provided a body of data which showed that 2-3% increase in fuel efficiency was obtained when the 15/590 was used in diesel powered trucks. The equation for sonically choked flow,

two in. H_2O can invalidate the test results. When the space velocity is reduced, the pressure loss will be reduced a certain extent, however, not entirely. The rough shaped vermiculite tends to become packed and block the flow for any bed thickness.

In order to achieve the high reductions obtained in other studies it is necessary to coat the vermiculite with a chemical containing ammonia. The cost of the thiourea (which has given up to 98% NO_x reduction) is quite high when purchased in the quantities needed for a test cell. A 2 Kg box cost \$50.

B. ADDITIVE STUDIES

The additive testing occurred after the NO_x testing. During the additive studies the T-63 was reconfigured for maximum soot production by installing the quench, reducing main air pressure to 600 psi and connecting the window purge gas. Two data runs were made with the augmentor tube removed, additive pumps installed and calibrated, IR camera positioned, and laser installed. In both runs all parameters were kept the same with the exception of the additive. The following effects of the additives were measured: plume opacity (soot concentration assuming D_{32} constant), burner efficiency, and temperature distribution within the exhaust plume. NAPC 3 fuel was used for all runs.

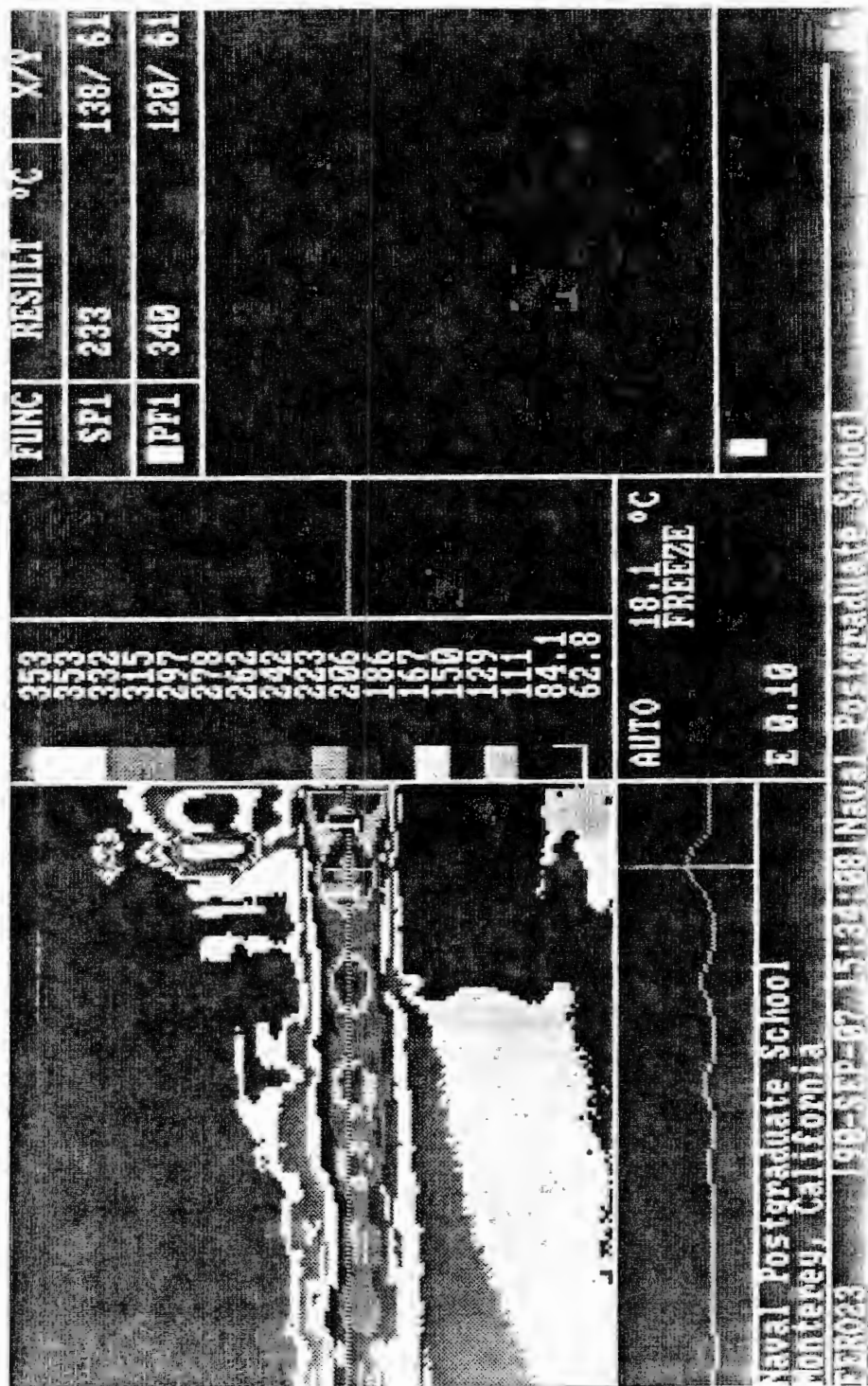


Figure 11 Plume w/o Catane

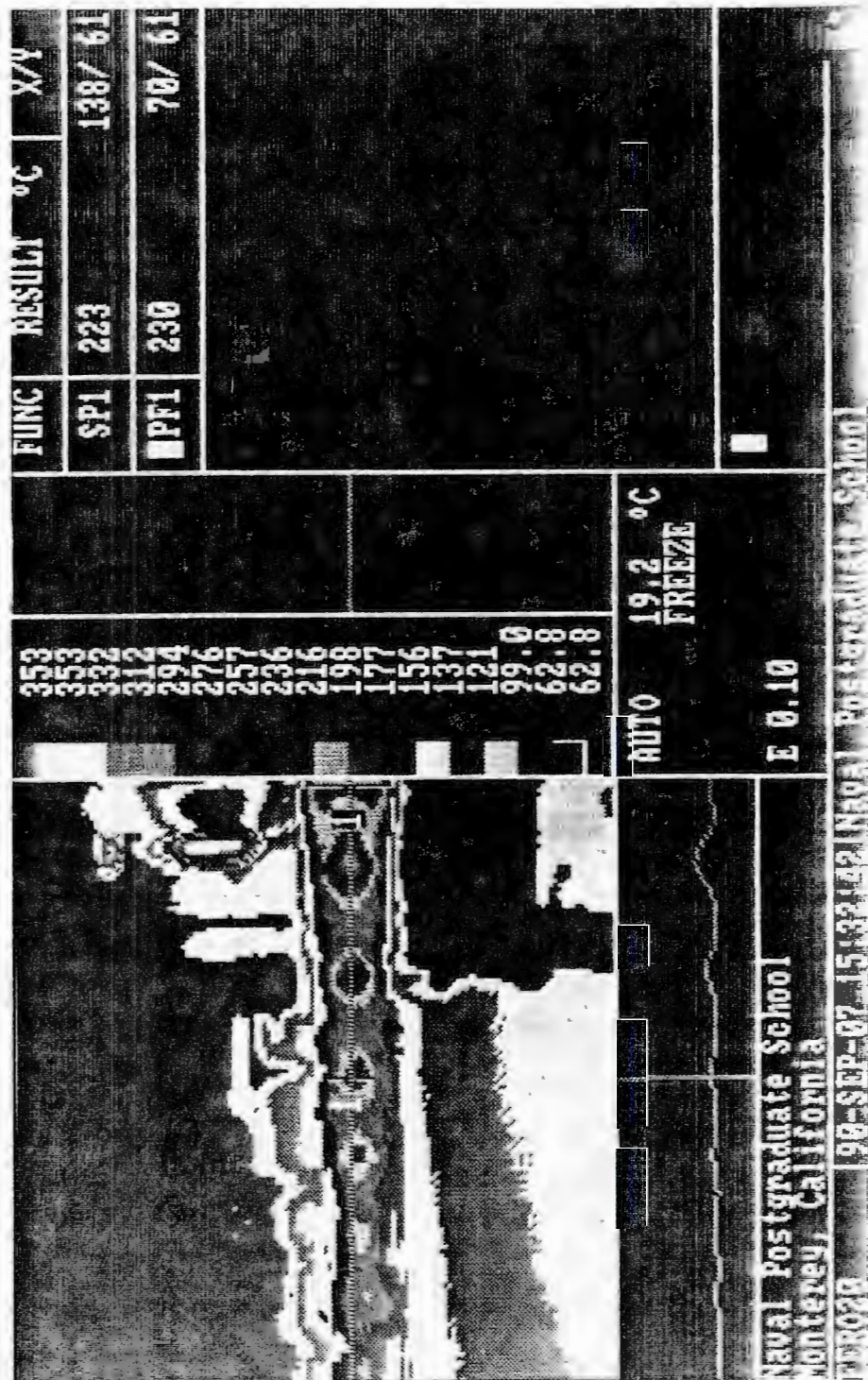
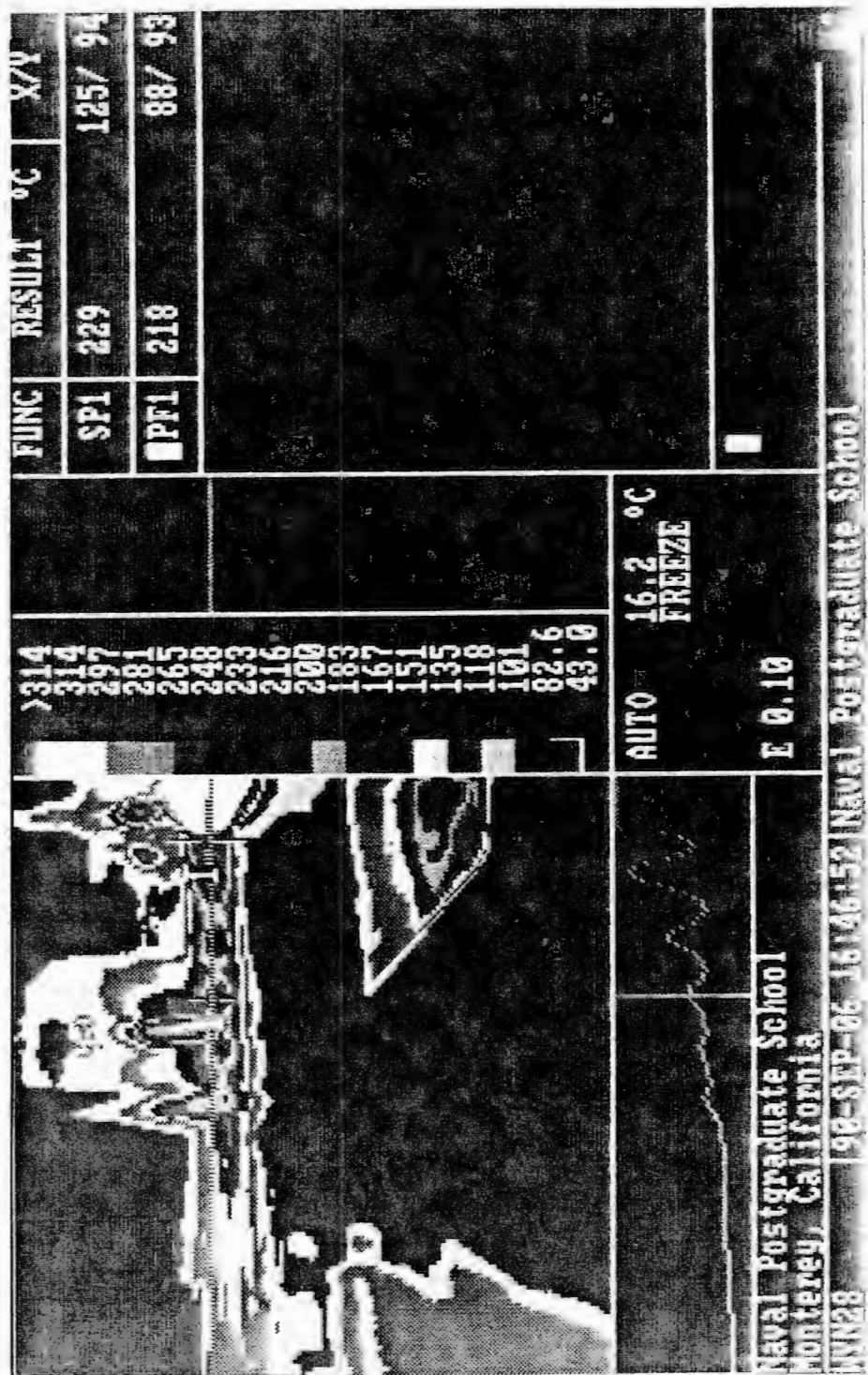


Figure 12 Plume with Catane TM



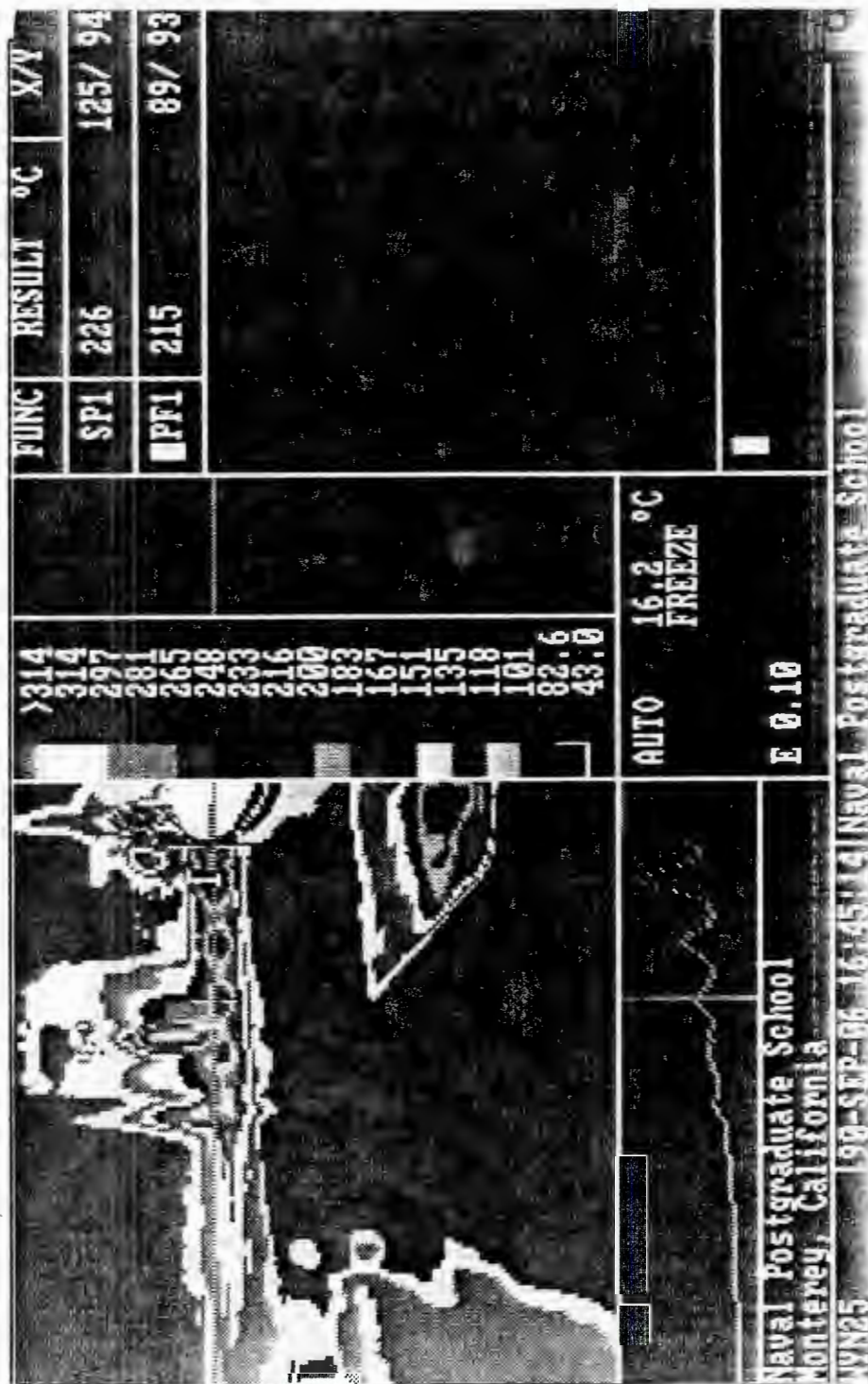


Figure 14 Plume with 15/590

The temperature measured at the nozzle entrance, T_{ex2} , was higher than the value expected. It was surmised that the thermocouple was located in a hot recirculation zone and yielded abnormally high temperatures. Using an energy balance for the combustor and quench air flows an average " T_{mix} " could be calculated. This yielded a lower "effective" T_{ex2} , but still not as low as expected from the plume temperature measurement. It was noted following every run that the combustor was quite hot, in fact it frequently glowed dull red during a run. These heat losses are believed to account for much of the lower than expected plume temperatures. In addition, the exact emissivity of the gas could not be set in the Agema system. This variance from the correct value is discussed below and caused the temperatures read from the IR system to be somewhat low.

Although every effort was made to maintain steady flow rates during the run, there were small changes in the air and fuel flows during the approximately five minute run. These were probably due to temperature changes and pressure regulator drifts. These changes in fuel-air ratio (f) can be seen in Appendix D. In order to properly compare the plume temperatures obtained with and without the additive, a correction was required to put them on the same f basis. An equilibrium adiabatic combustion code was used [Ref. 17]. Micro NewPEP was run several times using JP4 with values of f around the values actually observed. This gave the approximate

theoretical temperature at the throat of the choked exhaust nozzle. Approximate values of $\Delta T^* / \Delta f$ were then generated to provide corrections of the measured temperature data to the same value of f .

The IR pictures generated were analyzed with the spotmeter function at the same pixel location of the image, both with and without the additive. The location chosen was the throat of the converging exhaust nozzle. The differences were calculated and are summarized in Table V.

TABLE VI SUMMARY OF IR MEASUREMENTS

Condition Fig. No.	f	$T_{mix} \text{ } ^\circ\text{C}$	$T_{ex2} \text{ } ^\circ\text{C}$	$T^* \text{ } ^\circ\text{C},$ IR camera
w/o Catane Fig. 13	0.0171	475	521	233
Catane TM Fig. 14	0.0163	458	504	223
$\Delta T^* \text{ } ^\circ\text{C}$ ($T^*_{w/o} - T^*_w$) measured				+10
$\Delta T^* \text{ } ^\circ\text{C}$ for same f , expected				+26

Condition Fig. No.	f	T _{mix} °C	T _{ex2} °C	T* °C, IR camera
w/o 15/590 Fig. 15	0.0169	456	505	229
15/590 Fig. 16	0.017	460	511	226
$\Delta T^* \text{ } ^\circ\text{C}$ (T*w/o-T*w) measured				+3
$\Delta T^* \text{ } ^\circ\text{C}$ for same f, expected				+3

The emissivity of the exhaust plume must be known for exact temperatures to be displayed on the image. The emissivities of CO₂ and H₂O are each approximately 0.06 for a 4 in. diameter nozzle at 1000°F [Ref. 17]. However, the Agema system can not be set below 0.1. Using 0.06 would further increase the measured temperature of the plume to values closer to the values expected from the nozzle flow. There are, of course, many other species in the exhaust plume. However, they are weak emitters.

In the run with the Catane additive, it was expected that the temperature would decrease from 233° C to 207° C for

the conditions without the additive, based on the changes in f alone. However, it was measured that the temperature decreased to only 223° C. Therefore, when the data were corrected to the same f value, the plume IR signature actually increased slightly.

The temperatures for the Wynn's 15/590 tests were expected to remain almost constant for the condition with the additive, based on changes in f alone. Yet, the measurements showed that the temperature decreased slightly (3° C). These slight changes were within the realm of data uncertainty and there was considered to be no significant change in the plume thermal distribution.

V. CONCLUSIONS AND RECOMMENDATIONS

A. NO_x REDUCTION

With the pressure loss experienced in the present work, and by Behrens, it can be concluded that vermiculite in the form utilized will not be effective in reducing the NO_x emissions from US Navy or US Air Force test cells. In addition, much larger surface areas will be required with extensive modification to the existing structures. If the vermiculite could be formed into a honeycomb shape it might be possible to reduce the pressure loss. There is still the problem of reducing the space velocity in order to increase the NO_x reduction effectiveness. Even a SCR system will require enlargement of the augmentor tube to accommodate the increased volume of the catalyst bed. Future effort might be directed at developing a larger catalyst bed with custom-formed large size vermiculite. The effectiveness and amount of slip from a SCR system should be investigated under military test cell applications.

B. ADDITIVE STUDIES

In the T-63 combustor, the Wynn's 15/590 was ineffective in reducing the soot. It also had no effect on the efficiency

of the combustor. This was not entirely unexpected since the efficiency of this combustor was already quite high.

When all factors such as heat losses and emissivity corrections are taken into account, the Agema IR Imaging System can give accurate nonintrusive measurements of jet exhaust stream thermal distributions.

Neither of the additives tested were effective in reducing the IR signature of a ramjet type exhaust plume. It is recommended that further study be carried out to investigate the effects of different fuels and different additive mixture ratios on the plume IR signature.

APPENDIX A

"T63NOX" Computer program

```

10 ! T63 VERSION 9, JAN 1990
20 ! PRINTER IS 1
30 ! T63 COMBUSTOR DATA ACQUISITION AND REDUCTION PROGRAM
40 ! THIS PROGRAM IS DIVIDED INTO FIVE PARTS:
50 !     (1) VARIABLE DEFINITIONS AND NOMENCLATURE
60 !     (2) TRANSDUCER CALIBRATIONS
70 !     (3) FLOW CHECKS AND NOZZLE CALCULATIONS
80 !     (4) THE TEST SEQUENCE AND DATA COLLECTION
90 !     (5) POST-RUN OPERATIONS, DATA REDUCTION AND SHUTDOWN
100 ! *****
110 ! (1) VARIABLE DEFINITIONS AND NOMENCLATURE
120 ! *****
130 ! SYMROL      DEFINITION
140 ! A           ANALOG CHANNEL NUMBER
150 ! Aair        THROAT AREA, AIR FLOW SONIC CHOKE, SQ. IN.
160 ! Ahf         THROAT AREA, HEATER FUEL SONIC CHOKE, SQ. IN.
170 ! Aho         THROAT AREA, HEATER OXYGEN SONIC CHOKE, SQ. IN.
180 ! Bpair       BYPASS AIR FLOWRATE
190 ! Cdair       DISCHARGE COEFFICIENT, AIR SONIC CHOKE
200 ! Cdhf        DISCHARGE COEFFICIENT, HEATER FUEL SONIC CHOKE
210 ! Cdho        DISCHARGE COEFFICIENT, HEATER O2 SONIC CHOKE
220 ! Dairchoke   AIR SONIC CHOKE DIAMETER
230 ! Dbpchoke    BYPASS AIR SONIC CHOKE DIAMETER
240 ! Date$       Test Date Mo-Day-Yr
250 ! Dhfchoke    AIR HEATER FUEL SONIC CHOKE DIAMETER
260 ! Dhochoke    AIR HEATER OXYGEN SONIC CHOKE DIAMETER
270 ! Fuelid$     FUEL IDENTIFICATION
280 ! Gc          32.174
290 ! Gc=32.174
300 ! Heaterfuel  HEATER FUEL IDENTIFICATION
310 !
320 ! Kmair       AIR SONIC CHOKE FLOW RATE CONSTANT
330 ! Kmfuel      FUEL FLOW METER RATE CONSTANT (GPM/VOLT)
340 ! Kmhf        HEATER FUEL SONIC CHOKE FLOW RATE CONSTANT
350 ! Kmho        HEATER O2 SONIC CHOKE FLOW RATE CONSTANT
360 ! Kp          PRESSURE TRANSDUCERS CONSTANT (PSI/VOLT)
370 ! Maair       AIR FLOW RATE, LBM/SEC
380 ! Maaird      DESIRED AIR FLOW RATE, LBM/SEC
390 ! Mfuel       FUEL FLOW RATE, GPM
400 ! Mfueld      DESIRED FUEL FLOW RATE, GPM
410 ! Mhf         HEATER FUEL FLOW RATE, LBM/SEC
420 ! Mhfd        DESIRED HEATER FUEL FLOW RATE LBM/SEC
430 ! Mho         HEATER OXYGEN FLOW RATE, LBM/SEC
440 ! Mhod        DESIRED HEATER OXYGEN FLOW RATE, LBM/SEC
450 ! Pa          PRESSURE, AIR SONIC CHOKE, PSIA
460 ! Pbp         PRESSURE, BYPASS AIR SONIC CHOKE, PSIA
470 ! Pbar        BAROMETRIC PRESSURE, PSIA
480 ! Pc          PRESSURE, COMBUSTION CHAMBER, PSIA
490 ! Phf         PRESSURE, HEATER FUEL SONIC CHOKE, PSIA
500 ! Pho         PRESSURE, HEATER OXYGEN SONIC CHOKE, PSIA
510 ! Ta          TEMPERATURE, AIR SONIC CHOKE, R
520 ! Tbp         TEMPERATURE, BYPASS AIR SONIC CHOKE, R
530 ! Tavgup      TEMPERATURE, AUGMENTOR TUBE UPSTREAM CATALYST, R
540 ! Tavgdl      TEMPERATURE, AUGMENTOR TUBE DOWNSTREAM CATALYST, R
550 ! Testno$     TEST I.D NO.
560 ! Thf         TEMPERATURE, HEATER FUEL SONIC CHOKE, R
570 ! Tho         TEMPERATURE, HEATER O2 SONIC CHOKE, R
580 ! Tcin        TEMPERATURE, COMBUSTOR AIR INLET (HEATER OUTLET), R
590 ! Tcind       TEMPERATURE, DESIRED COMBUSTOR AIR INLET, R
600 ! Tex1        TEMPERATURE, COMBUSTOR EXHAUST UPSTREAM OF QUENCH, R
610 ! Tex2        TEMPERATURE, COMBUSTOR EXHAUST DOWNSTREAM OF QUENCH, R
620 BEEP 1000,.1
630 PRINT USING "@ "
640 PRINT USING "6/"

```

```

650 PRINT " T63 DATA ACQUISITION "
660 PRINT USING "5/"
670 PRINT "TURN THE PRINTER ON LINE"
680 CLEAR 709
690 CLEAR 722
700 ! THE RECORDED VARIABLES (VOLTAGES) AND LOCATIONS ARE:
710 ! (NOTE: THE MAXIMUM ALLOWABLE VOLTAGE INTO THE SYSTEM IS 1.2 VOLTS)
720 !
730 ! VARIABLE                                3497 DACU SCANNER NUMBER 0__
740 !
750 ! Pa----- 24-----
760 ! Pbp3 24
770 ! Pc 23
780 ! Mfuel 25
790 ! Phf 22
800 ! Phg 21
810 ! Ta 60
820 ! Tcin (inlet air) 61
830 ! Tex1 (upstream of quench) 62
840 ! Tex2 (downstream of quench) 63
850 ! Tho 64
860 ! Thf 65
870 ! Tavgup 66
880 ! Tavgd1 67
890 ! Tavgd2 68
900 ! ALL FLOW RATES ARE CALCULATED USING THE ONE-DIMENSIONAL, ISENTROPIC
910 ! FLOW EXPRESSIONS WITH FIXED PROPERTIES. SMALL SONIC NOZZLES HAVE
920 ! MEASURED DISCHARGE COEFFICIENTS. THE AIR FLOW NOZZLE USES AN ASSUMED
930 ! DISCHARGE COEFFICIENT (Cd) OF 0.97.
940 !
950 ! M (LBM/SEC)=Cd*P*A*Km/T^.5
960 !
970 ! Km IS THE GAS-DEPENDENT SONIC CHOKE FLOW RATE CONSTANT
980 !
990 ! Km=SQR((Gamma*Gc/R)*(2/(Gamma+1))^(Gamma+1)/(Gamma-1)))
1000 !
1010 ! APPROPRIATE CONSTANTS ARE:
1020 !
1030 ! GAS      MOLECULAR WT.   GAS CONST.   CP      GAMMA   Km
1040 !
1050 ! AIR      28.97          53.3         .240    1.40    .5320
1060 ! O2       32.0           48.3         .217    1.40    .5589
1070 ! CH4      16.03          96.4         .593    1.32    .3876
1080 ! N2       28.01          55.16        .248    1.40    .5229
1090 ! H2       2.016         766.5        3.419   1.405   .1405
1100 !
1110 Gammaair=1.40
1120 Gammaox=1.40
1130 Gammahf=1.405
1140 Kmair=.5320
1150 Kmho=.5589
1160 Kmhf=.1405
1170 Rair=53.3
1180 Rho=48.3
1190 Rhf=766.5
1200 Dairchoke=.42
1210 Dbpchoke=.239
1220 Dhochoke=.0700
1230 Dhfchoke=.040
1240 Maird=.9
1250 Mbpaird=.59
1260 Mfuel=.33
1270 Mhfd=.00285
1280 Mhod=.0228
1290 PRINT USING "6/"
1300 INPUT "Input the barometric pressure in mm of Hg",Pmm
1310 Pbar=Pmm*.019337
1320 Cdair=.97
1330 Cdhf=.97
1340 Cdhm=.97

```

```

1350 !ALL THERMOCOUPLES ARE CHROMEL vs. ALUMEL (TYPE K) WITH
1360 !ELECTRONIC ICE POINTS. TEMPERATURE READINGS (VOLTAGES) ARE
1370 !CONVERTED TO DEGREES RANKINE (R) PER "INDUSTRIAL INSTRUMENTATION" BY
1380 !D.P. ECKMAN (PAGE 369). THIS CALCULATION IS PERFORMED IN SUBROUTINE
1390 !Tcalc. TEN VOLTAGE INTERVALS ARE USED BETWEEN 460 AND 2460 R.
1400 PRINT USING "E"
1410 PRINT USING "6/"
1420 INPUT "WILL THE AUGMENTOR TUBE BE USED? (Y/N)",Aug$
1430 IF Aug$="Y" THEN Aug=1
1440 IF Aug$="N" THEN Aug=0
1450 PRINT USING "E"
1460 PRINT USING "6/"
1470 INPUT "WILL THE AIR HEATER BE USED? (Y/N)",Zz$
1480 IF Zz$="Y" THEN Ht=1,
1490 IF Zz$="N" THEN Ht=0,
1500 PRINT USING "E"
1510 PRINT USING "6/"
1520 INPUT "WILL YOU USE PRE-INITIALIZED VALUES OF CALIBRATION CONSTANTS AND ZE
ROS? (Y/N)",Zz$
1530 IF Zz$="Y" THEN GOTO Initial
1540 GOTO Transcal
1550 Tcalc: !
1560 !*****
1570 ! ***VOLTAGE TO TEMPERATURE (RANKINE) CONVERSION SUBROUTINE***
1580 !*****
1590 IF Volts<.00153 THEN T=((Volts+.00068)/.0000220)+460
1600 IF Volts=.00153 AND Volts<.00382 THEN T=((Volts-.00153)/.000022
0)+560
1610 IF Volts=.00382 AND Volts<.00609 THEN T=((Volts-.00382)/.000022
7)+660
1620 IF Volts=.00609 AND Volts<.00831 THEN T=((Volts-.00609)/.000022
2)+760
1630 IF Volts=.00831 AND Volts<.01056 THEN T=((Volts-.00831)/.000022
5)+860
1640 IF Volts=.01056 AND Volts<.01285 THEN T=((Volts-.01056)/.000022
9)+960
1650 IF Volts=.01285 AND Volts<.01518 THEN T=((Volts-.01285)/.000023
3)+1060
1660 IF Volts=.01518 AND Volts<.01752 THEN T=((Volts-.01518)/.000023
4)+1160
1670 IF Volts=.01752 AND Volts<.01988 THEN T=((Volts-.01518)/.000023
IF Volts=.01988 AND Volts<.02225 THEN T=((Volts-.01988)/.000023
IF Volts=.02225 AND Volts<.02463 THEN T=((Volts-.02225)/.000023
IF Volts=.02463 AND Volts<.02698 THEN T=((Volts-.02463)/.000023
IF Volts=.02698 AND Volts<.02932 THEN T=((Volts-.02698)/.000023
IF Volts=.02932 AND Volts<.03165 THEN T=((Volts-.02932)/.000023
IF Volts=.03165 AND Volts<.03393 THEN T=((Volts-.03165)/.000022
IF Volts=.03393 AND Volts<.03619 THEN T=((Volts-.03393)/.000022
IF Volts=.03619 AND Volts<.03843 THEN T=((Volts-.03619)/.000022
IF Volts=.03843 AND Volts<.04062 THEN T=((Volts-.03843)/.000021
IF Volts=.04062 AND Volts<.04278 THEN T=((Volts-.04062)/.000021
IF Volts=.04278 AND Volts<.04491 THEN T=((Volts-.04278)/.000021
IF Volts=.04491 THEN T=((Volts-.04278)/.0000216)+2460
1790
1800 RETURN
1810 Initial: !
1820 ! Initialized values of zeros and calibration constants for all transducers

```

```

1830 Testno$="KURT1"
1840 Date$="8-01-90"
1850 Fuelid$="NAPC4"
1860 Heaterfuel$="HYDROGEN"
1870 Vpa0=.0017222
1880 Kpa=33368.37
1890 Vpc0=-.176573
1900 Kpc=845.73678
1910 Vpho0=.0356869
1920 Kpho=671.61413
1930 Vphf0=-.116253
1940 Kphf=1356.9702
1950 Kmfuel=.5
1960 Transcal: !
1970 !*****
1980 !(2) TRANSDUCER CALIBRATIONS
1990 !*****
2000 !THERE ARE 4 PRESSURE TRANSDUCERS THAT MUST BE CALIBRATED
2010 !TRANSDUCER LINEARITY MUST BE VERIFIED BEFORE THIS
2020 !CALIBRATION PROCEDURE IS EMPLOYED. THE ORDER OF CALIBRATION IS AS
2030 !FOLLOWS: Pa, Pc, Phf, Pho
2040 !THE FOLLOWING TWO LINES SET UP 722 AND 709 FOR DATA ACQUISITION"
2050 !CLEAR 709
2060 CLEAR 722
2070 REMOTE 709
2080 OUTPUT 722;"L1R11STNZ110STIT4QX1"
2090 INPUT "DO YOU WANT TO CALIBRATE TRANSDUCERS? (Y/N)",Yy$
2100 IF Yy$="N" THEN GOTO Endcal
2110 INPUT "DO YOU WANT CONSECUTIVE ORDER OF CALIBRATION?(Y/N)",Yy$
2120 IF Yy$="Y" THEN GOTO Consec
2130 INPUT "DO YOU WANT TO RECALIBRATE Pa? (Y/N)",Yy$
2140 IF Yy$="Y" THEN GOTO Pacal
2150 PRINT USING "E"
2160 Pc: !
2170 INPUT "DO YOU WANT TO RECALIBRATE Pc? (Y/N)",Yy$
2180 IF Yy$="Y" THEN GOTO Pccal
2190 PRINT USING "E"
2200 IF Ht=0 THEN GOTO Endcal
2210 Phf: !
2220 INPUT "DO YOU WANT TO RECALIBRATE Phf? (Y/N)",Yy$
2230 IF Yy$="Y" THEN GOTO Phfcal
2240 PRINT USING "E"
2250 Pho: !
2260 INPUT "DO YOU WANT TO RECALIBRATE Pho? (Y/N)",Yy$
2270 IF Yy$="Y" THEN GOTO Phocal
2280 GOTO Endcal
2290 Consec: !
2300 Cons=1
2310 Pacal: !
2320 !*****
2330 PRINT USING "2/"
2340 PRINT "** CALIBRATION OF Pa, THE AIR SONIC CHOKE PRESSURE TRANSDUCER**"
2350 PRINT USING "2/"
2360 !*****

```

```

-----
2370 Pa0cal: !
2380 PRINT "***** Z E R O   P R E S S U R E *****"
2390 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2400 DISP "HIT CONTINUE WHEN READY TO TAKE ZERO READING"
2410 PAUSE
2420 REMOTE 709
2430 OUTPUT 709;"AC24"
2440 WAIT 2
2450 OUTPUT 722;"T3"
2460 ENTER 722;Vpa0
2470 PRINT "Vpa0=";Vpa0
2480 BEEP
2490 INPUT "READING OK? (Y/N)",Zz$
2500 IF Zz$="N" THEN GOTO Pa0cal
2510 Pamaxcal: !
2520 PRINT USING "E"
2530 PRINT "***** C A L I B R A T I O N *****"
2540 PRINT "APPLY MAXIMUM PRESSURE USING THE DEAD-WEIGHT TESTER"
2550 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pamax
2560 DISP "HIT CONTINUE WHEN READY"
2570 PAUSE
2580 REMOTE 709
2590 OUTPUT 709;"AC24"
2600 WAIT 2
2610 OUTPUT 722;"T3"
2620 ENTER 722;Vpamax
2630 PRINT "Vpamax=";Vpamax,"Pamax=";Pamax
2640 Kpa=(Pamax)/(Vpamax-Vpa0)
2650 PRINT "Kpa=";Kpa
2660 BEEP
2670 INPUT "READING OK? (Y/N)",Zz$
2680 IF Zz$="N" THEN GOTO Pamaxcal
2690 IF Cons=1 THEN GOTO Pccal
2700 Pccal: !
2710 !*****
2720 PRINT USING "E"
2730 PRINT "CALIBRATION OF Pc, THE T63 CHAMBER PRESSURE TRANSDUCER**"
2740 !*****
2750 Pc0cal: !
2760 PRINT "***** ZERO PRESSURE *****"
2770 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2780 DISP "HIT CONTINUE WHEN READY"
2790 PAUSE
2800 REMOTE 709
2810 OUTPUT 709;"AC23"
2820 WAIT 2
2830 OUTPUT 722;"T3"
2840 ENTER 722;Vpc0
2850 PRINT "Vpc0=";Vpc0

```

```

2860 BEEP
2870 INPUT "READING OK? (Y/N)",Zz$
2880 IF Zz$="N" THEN GOTO Pc0cal
2890 Pcmaxcal: !
2900 PRINT USING "@"
2910 PRINT "**** CALIBRATION ****"
2920 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2930 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pcmax
2940 DISP "HIT CONTINUE WHEN READY"
2950 PAUSE
2960 REMOTE 709
2970 OUTPUT 709;"AC23"
2980 WAIT 2
2990 OUTPUT 722;"T3"
3000 ENTER 722;Vpcmax
3010 PRINT "Vpcmax=";Vpcmax,"Pcmax=";Pcmax
3020 Kpc=Pcmax/(Vpcmax-Vpc0)
3030 PRINT "Kpc=";Kpc
3040 BEEP
3050 INPUT "READING OK? (Y/N)",Zz$
3060 IF Zz$="N" THEN GOTO Pcmaxcal
3070 IF Ht=0. THEN GOTO Fincal
3080 IF Cons=1 THEN GOTO Phfcal
3090 GOTO Phf
3100 Phfcal: !
3110 !*****
3120 PRINT USING "@"
3130 PRINT "**CALIBRATION OF Phf , THE T63 AIR HEATER FUEL TRANSDUCER**"
3140 !*****
3150 Phf0cal: !
3160 PRINT "****ZERO PRESSURE****"
3170 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3180 DISP "HIT CONTINUE WHEN READY"
3190 PAUSE
3200 REMOTE 709
3210 OUTPUT 709;"AC22"
3220 WAIT 2
3230 OUTPUT 722;"T3"
3240 ENTER 722;Vphf0
3250 PRINT "Vphf0=";Vphf0
3260 BEEP
3270 INPUT "READING OK? (Y/N)",Zz$
3280 IF Zz$="N" THEN GOTO Phf0cal
3290 Phfmaxcal: !
3300 PRINT USING "@"
3310 PRINT "****CALIBRATION****"
3320 DISP "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3330 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phfmax
3340 DISP "HIT CONTINUE WHEN READY"
3350 PAUSE
3360 REMOTE 709
3370 OUTPUT 709;"AC22"
3380 WAIT 2
3390 OUTPUT 722;"T3"
3400 ENTER 722;Vphfmax
3410 PRINT "Vphfmax=";Vphfmax,"Phfmax=";Phfmax
3420 Kphf=Phfmax/(Vphfmax-Vphf0)
3430 PRINT "Kphf=";Kphf
3440 BEEP
3450 INPUT "READING OK? (Y/N)",Zz$
3460 IF Zz$="N" THEN GOTO Phfmaxcal
3470 IF Cons=1 THEN GOTO Phocal
3480 GOTO Phf
3490 Phocal: !
3500 !*****
3510 PRINT USING "@"
3520 PRINT "**CALIBRATION OF Phf, THE AIR HEATER OXYGEN PRESSURE TRANSDUCER**"
3530 !*****

```

```

3540 Pho0cal: !
3550 PRINT "****ZERO CALIBRATION****"
3560 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3570 DISP "HIT CONTINUE WHEN READY"
3580 PAUSE
3590 REMOTE 709
3600 OUTPUT 709;"AC21"
3610 OUTPUT 722;"T3"
3620 ENTER 722;Vpho0
3630 PRINT "Vpho0=";Vpho0
3640 INPUT "READING OK? (Y/N)",Zz$
3650 IF Zz$="N" THEN GOTO Pho0cal
3660 Phomaxcal: !
3670 PRINT USING "@"
3680 PRINT "****CALIERATION****"
3690 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3700 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phomax
3710 DISP "HIT CONTINUE WHEN READY"
3720 PAUSE
3730 REMOTE 709
3740 OUTPUT 709;"AC21"
3750 OUTPUT 722;"T3"
3760 ENTER 722;Vphomax
3770 PRINT "Vphomax=";Vphomax,"Phomax=";Phomax
3780 Kpho=Phomax/(Vphomax-Vpho0)
3790 PRINT "Kpho=";Kpho
3800 BEEP
3810 INPUT "READING OK? (Y/N)",Zz$
3820 IF Zz$="N" THEN GOTO Phomaxcal
3830 IF Aug=1 THEN GOTO Augcal
3840 Endcal: !
3850 Fincal: !
3860 PRINT USING "@"
3870 PRINT "THIS ENDS THE CALIBRATIONS "
3880 !*****
3890 !(3) PRE-RUN INPUTS, FLOW RATE CHECKS AND NOZZLE CALCULATIONS
3900 !*****
3910 !*****
3920 ! A. FLOW RATE SET-UPS AND CHECKS
3930 !*****
3940 PRINT USING "@"
3950 INPUT "DO YOU WANT TO PRESET THE AIR FLOW RATE?(Y/N)",Zz$
3960 IF Zz$="N" THEN GOTO Paskip
3970 PRINT "SET THE DESIRED VALUE OF Pa(psig) USING THE HAND LOADER /PRESSURE G
AGE"
3980 PRINT USING "3/"
3990 PRINT "THE HAND LOADER SHOULD BE 20 PSIG MORE THAN DESIRED PRESSURE"
4000 Paset: !
4010 PRINT USING "3/"
4020 PRINT "MANUALLY INITIATE AIR FLOW BY TURNING 'MAIN AIR' ON CONTROL PANEL"
4030 PRINT USING "2/"
4040 DISP "HIT CONTINUE WHEN READY"
4050 PAUSE
4060 WAIT 3
4070 OUTPUT 709;"AC24"
4080 OUTPUT 722;"T3"
4090 ENTER 722;Vpa
4100 OUTPUT 709;"AC60"
4110 OUTPUT 722;"T3"
4120 ENTER 722;Vta
4130 OUTPUT 709;"AC61"
4140 OUTPUT 722;"T3"
4150 ENTER 722;Vti
4160 BEEP
4170 PRINT USING "@"
4180 PRINT "TURN OFF 'MAIN AIR'"
4190 DISP "HIT CONTINUE TO PROCEED"
4200 PAUSE
4210 Pa=(Vpa-Vpa0)*Kpa+Pbar
4220 Volts=Vta
4230 cnsig T-1-1-

```

```

4240 Ta=T
4250 Volts=Vti
4260 GOSUB Tcalc
4270 Tcin=T
4280 Mair=Kmair*Cdair*Pa*.7854*(Dairchoke2)/(Ta.5)
4290 Bpair=Kmair*Cdair*Pa*.7854*(Dbpcchoke2)/(Ta.5)
4300 PRINT USING "E"
4310 PRINT USING "5A,2X,DDD.DDDD";"Mair=";Mair
4320 PRINT USING "14A,DDD.DDD";"Mair DESIRED=";Maird
4330 Ratio=Mair/Maird
4340 PRINT USING "20A,D,DDD,2X,3A,1X,DDDD.D,1A,3X,3A";"Mair/DESIRED Mair=";Ratio
4350 Ta="";Ta,"R"
4360 PRINT USING "6A,2X,DDD.DDDD";"Bpair=";Bpair
4370 Pg=Pa-Pbar
4380 PRINT USING "4A,DDDD.D,6A";"Pa=";Pg;" Psig"
4390 PRINT USING "4A,DDDD.D,3A";"Ta=";Ta;" R"
4390 INPUT "IS AIR FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
4400 IF Xx$="Y" THEN GOTO Prerun
4410 Panew=(Pa*Maird/Mair)-Pbar
4420 PRINT "RESET Pa TO";Panew;"Psig"
4430 DISP "HIT CONTINUE AFTER RESET OF Pa"
4440 PAUSE
4450 GOTO Paset
4460 Prerun:
4470 INPUT "DO YOU WANT PRINTOUT OF PRE-RUN DATA?(Y/N)",Xx$
4480 IF Xx$="Y" THEN GOTO Preprint
4490 GOTO Skipprint
4500 Preprint:
4510 PRINTER IS 701
4520 PRINT "          **** PRE-RUN DATA, USING AIR ONLY ****"
4530 PRINT ""
4540 PRINT "DATE: ";Date$
4550 PRINT USING "3A,DDDD.D,6A";"Pa=";Pa;" Psia"
4560 PRINT USING "3A,DDD.D,3A";"Tcin=";Tcin;" R"
4570 PRINT USING "5A,D,DDDD,11A";"Mair=";Mair;" (lbm/sec)"
4580 PRINT USING "5A,D,DDDD,11A";"Bpair=";Bpair;" (lbm/sec)"
4590 PRINTER IS 1
4600 Skipprint:
4610 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
4620 PAUSE
4630 Paskip:
4640 IF Ht=0 THEN GOTO Phoskip
4650 PRINT USING "E"
4660 INPUT "DO YOU WANT TO PRESET THE HEATER FUEL FLOW RATE? (Y/N)",Zz$
4670 IF Zz$="N" THEN GOTO Phfskip
4680 !*****
4690 PRINT "SET THE DESIRED VALUE OF Phf USING THE HAND LOADER/PRESSURE GAGE"
4700 !*****
4710 DISP "HIT CONTINUE WHEN READY"
4720 PAUSE
4730 Phfset:
4740 PRINT USING "E"
4750 PRINT "MANUALLY TURN ON AIR 'HEATER FUEL' SWITCH"
4760 DISP "HIT CONTINUE TO PROCEED"
4770 PAUSE
4780 OUTPUT 709;"AC22"
4790 OUTPUT 722;"T3"
4800 ENTER 722;Vphf
4810 OUTPUT 709;"AC65"
4820 OUTPUT 722;"T3"
4830 ENTER 722;Vthf
4840 !CLEAR 709
4850 PRINT "MANUALLY TURN OFF AIR 'HEATER FUEL' SWITCH"
4860 BEEP
4870 DISP "HIT CONTINUE TO PROCEED"
4880 PAUSE
4890 Phf=(Vphf-Vphf0)*Kphf+Pbar
4900 Volts=Vthf
4910 GOSUB Tcalc
4920 Thf=T
4930 Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke2)/(Thf.5)

```

```

4940 PRINT USING "E"
4950 PRINT USING "4A,DD.DDDD"; "Mhf="; Mhf
4960 PRINT USING "12A,DD.DDDD"; "Mhf DESIRED="; Mhfd
4970 Ratio=Mhf/Mhfd
4980 PRINT USING "18A,D.DDD,2X,4A,DDDD.DD,1A"; "Mhf/ Mhf DESIRED="; Ratio, "Thf="
;Thf, "R"
4990 Pg=Phf-Pbar
5000 PRINT USING "5A,DDDD.DDD,4A,3X,4A,DDDD.DD,1A,4A,DDDD.DD,1A"; "Phf= "; Pg; "P
sig", "Thf="; Thf; "R"
5010 INPUT "IS HEATER FUEL FLOW RATE ACCURATE ENOUGH? <Y/N>", Xx$
5020 IF Xx$="Y" THEN GOTO Phffin
5030 Phfnew=(Phf*Mhfd/Mhf)-Pbar
5040 PRINT USING "13A,DDDD.DD,4A"; "RESET Phf TO"; Phfnew; "Psig"
5050 DISP "HIT CONTINUE AFTER RESET OF Phf"
5060 PAUSE
5070 GOTO Phfset
5080 Phffin:
5090 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
5100 PAUSE
5110 Phfskip:
5120 PRINT USING "E"
5130 INPUT "DO YOU WANT TO PRESET THE HEATER OXYGEN FLOW RATE?<Y/N>", Zz$
5140 IF Zz$="N" THEN GOTO Phoskip
5150 !*****
5160 PRINT "SET THE DESIRED VALUE OF Pho USING THE HAND LOADER/PRESSURE GAGE"
5170 !*****
5180 Phoset:
5190 PRINT "MANUALLY TURN ON AIR 'HEATER OXYGEN' SWITCH"
5200 DISP "HIT CONTINUE TO PROCEED"
5210 PAUSE
5220 OUTPUT 709; "AC21"
5230 OUTPUT 722; "T3"
5240 ENTER 722; Vpho
5250 OUTPUT 709; "AC64"
5260 OUTPUT 722; "T3"
5270 ENTER 722; Vtho
5280 PRINT "MANUALLY TURN OFF AIR 'HEATER OXYGEN' SWITCH"
5290 BEEP
5300 DISP "HIT CONTINUE TO PROCEED"
5310 PAUSE
5320 Pho=(Vpho-Vpho0)*Kpho+Pbar
5330 Volts=Vtho
5340 GOSUB Tcalc
5350 Tho=T
5360 Mho=Kmo*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
5370 PRINT USING "E"
5380 PRINT USING "4A,DD.DDDD"; "Mho="; Mho
5390 PRINT USING "18A,DD.DDDD"; "Mho DESIRED="; Mhod
5400 Ratio=Mho/Mhod

```

```

5410      Pg=Pho-Pbar
5420      PRINT USING "5A,DDDD.DD,1X,5A,5X,4A,DDDD.DD,1X,2A";"Pho=";Pg;"Psig";
      "Tho=";Tho;"R"
5430      INPUT "IS THE HEATER OXYGEN FLOW RATE ENOUGH? (Y/N)?",Xx$
5440      IF Xx$="Y" THEN GOTO Phoskip
5450      Phonew=(Pho*Mhod/Mho)-Pbar
5460      PRINT USING "14A,DDDD.DD,1X,4A";"RESET Pho TO ";Phonew;"Psig"
5470      DISP "HIT CONTINUE AFTER RESET OF Pho"
5480      PAUSE
5490      GOTO Phoset
5500 Phoskip: !
5510      PRINT "THIS COMPLETES PRE-RUN SET-UP"
5520 !*****
5530 ! (4) THIS PORTION OF THE PROGRAM RUNS THE TEST AND COLLECTS THE DATA
5540 !*****
5550 ! PRINT USING "Q"
5560 DISP "SET TIMEDATE BY PRESSING K19 AND UPDATE, THEN EXECUTE, THEN HIT CON
      TINUE"
5570 BEEP
5580 PAUSE
5590 PRINT USING "Q"
5600 Rpt: !
5610      PRINTER IS 1
5620 ! THE FOLLOWING PROGRAMS THE 3456 DVM
5630 ASSIGN @Scanner TO 709
5640 ASSIGN @Svm TO 722
5650 CLEAR @Svm
5660 OPTION BASE 1
5670 DIM Press(10,5)
5680 DIM Temp(10,6)
5690 DIM Avgtemp(10,3)
5700 CLEAR @Svm
5710 OUTPUT @Svm;"L1Z1D0S0F1R30STD1STNP0FL01STIS01T401QX1"
5720 DISP "HIT CONTINUE FOR HOT RUN DATA"
5730 BEEP
5740 PAUSE
5750 DISP ""
5760 GOSUB Press
5770 GOSUB Tem
5780 IF Avg=1 THEN GOSUB Avg
5790 GOTO Shutdown
5800 !*****
5810 Press: !
5820 PRINT USING "Q"
5830 PRINT USING "10/"
5840 PRINT "***** COLLECTING PRESSURE *****"
5850 PRINT ""
5860 PRINT "***** COLLECTING PRESSURE *****"
5870 OUTPUT @Scanner;"AC21AF21AL25AE2"
5880 WAIT .2
5890 OUTPUT @Svm;"50STNT3"
5900 ENTER @Svm USING "#,K";Press(*)
5910 !
5920 OUTPUT @Svm;"1STNT4"
5930 RETURN
5940 !*****

```

SUBROUTINE Press

```

5740 *****
5950 Aug: ! TEMPERATURE COLLECTING ROUTINE FOR AUGMENTOR TUBE
5960 PRINT "*** COLLECTING AUGMENTOR TEMPERATURES ***"
5990 OUTPUT @Svm;"AC66AF66AL68AE2"
5991 OUTPUT @Svm;"30STNR2T3"
5992 WAIT .2
6000 ENTER @Svm USING "I,K";Augtemp(*)
6010 OUTPUT @Svm;"R31STNT4"
6020 RETURN
6030 !*****
6040 Ten: !
6050 PRINT "*****COLLECTING TEMPERATURES *****"
6060 OUTPUT @Svm;"60STNR2"
6070 OUTPUT @Scanner;"AC60AF60AL65AE2"
6080 WAIT .2
6090 OUTPUT @Svm;"60STNR2T3"
6100 ENTER @Svm USING "I,K";Temp(*)
6110 OUTPUT @Svm;"1STNR3T4"
6120 RETURN
6130 !*****
6140 Shutdown: !
6150 PRINT USING "E"
6160 PRINT " TEST COMPLETE: TURN OFF MAIN-AIR, HEATER GASES "
6170 !*****
6180 !* (5) POST-RUN OPERATION, DATA REDUCTION AND SHUTDOWN
6190 !*****
6200 DISP "HIT CONTINUE TO PROCEED TO DATA REDUCTION"
6210 KEEP
6220 PAUSE

```

```

6230 PRINT "PRINTER IS 701"
6240 PRINT USING "3/"
6250 PRINT "
6260 PRINT USING "2/"
6270 PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A"; "Testno="; Testno$, "Date="; Date$, '
Fuelid="; Fuelid$
6280 PRINT USING "14A,9A"; "Heaterfuel="; Heaterfuel$
6290 PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD"; "Dairchoke="; Dairchoke, "Dhtfuch
oke="; Dhfchoke
6300 PRINT USING "14A,DDDD.DDDD"; "Dhtoxchoke="; Dhoxchoke
6310 PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD,7X,14A,DDDD.DDE"; "Cdair="; Cdair,
"Cdh="; Cdhf, "Cdh="; Cdh
6320 PRINT USING "14A,DDDD.DDD,5X,14A,DDDD.DDD,5X,14A,DDDD.DDD"; "Gammahf="; Gamm
ahf
6330 PRINT USING "14A,DDDD.DD,5X,14A,DDDD.DD,5X,14A,DDDD.DD"; "Rh="; Rhf
6340 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD"; "Kmh="; Kmhf
6350 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD"; "Kmo="; Kmo, "Knair="; Knair
6360 PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.D"; "Maird="; Maird, "Icind="; Icind
6370 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,4X,14A,DDDD.D
DDD"; "Mhfd="; Mhfd, "Mhod="; Mhod, "Mfuel="; Mfuel
6380 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DD
D.DDDD"; "Kpa="; Kpa, "Vpa0="; Vpa0, "Kpc="; Kpc, "Vpc0="; Vpc0
6390 PRINT USING "3/"
6400 PRINT ""
6410 PRINT USING "35X,28A"; "**** DATA EXTRACTED ****"
6420 PRINT ""
6430 PRINT USING "120A"; "FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec,
PRESSURE IN Psia, TEMPERATURES IN R"
6440 PRINT USING "5A,6X,6A,5X,6A,7X,6A,9X,6(7A,5X)"; "Count", "Mair", "Mbpair
", "Mfuel", "f", "Mhf", "Mho", "Phf", "Pho", "Pc"
A d e n e r o t e t o l n

```

```

6460 Vpa=Press(J,4)
6470 Pa=(Vpa-Vpa0)*Kpa+Pbar
6480 Vpc=Press(J,3)
6490 Pc=(Vpc-Vpc0)*Kpc+Pbar
6500 Vmfuel=Press(J,5)
6510 Mfuel=Vmfuel*Kmfuel
6520 IF Ht=1 THEN
6530 Vphf=Press(J,2)
6540 Phf=(Vphf-Vphf0)*Kphf+Pbar
6550 Vpho=Press(J,1)
6560 Pho=(Vpho-Vpho0)*Kpho+Pbar
6570 END IF
6580 Volts=Temp(J,1)
6590 GOSUB Tcalc
6600 Ta=T
6610 IF Ht=1 THEN
6620 Volts=Temp(J,5)
6630 GOSUB Tcalc
6640 Tho=T
6650 Volts=Temp(J,6)
6660 GOSUB Tcalc
6670 Thf=T
6680 END IF
6690 !
6700 Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
6710 Bpair=Kmair*Cdair*Pa*.7854*(Dbpchoke^2)/(Ta^.5)
6720 F=.108*Mfuel/Mair
6730 IF Ht=0, THEN GOTO Jump
6740 IF Phf=(Pc*2) THEN Mhf=0.
6750 IF Pho=(Pc*2) THEN Mho=0.
6760 Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
6770 Mho=Kkho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
6780 Jump: !
6790 IF Ht=0, THEN
6800 Phf=0
6810 Pho=0
6820 Mhf=0
6830 Mho=0
6840 END IF
6850 ! THE VALUES BELOW ARE DEFAULT VALUES TO PREVENT PRINTER ERRORS
6860 IF Mair<.0001 THEN Mair=.0001
6870 IF Bpair<.0001 THEN Bpair=.0001
6880 IF Mfuel<.0001 THEN Mfuel=.0001
6890 IF F<.0001 THEN F=.0001
6900 IF Mhf<.0001 THEN Mhf=.0001
6910 IF Mho<.0001 THEN Mho=.0001
6920 IF Phf<.0001 THEN Phf=.0001
6930 IF Pho<.0001 THEN Pho=.0001
6940 IF Pc<.0001 THEN Pc=.0001
6950 IF Mair>2000. THEN Mair=2000.
6960 IF Bpair>2000. THEN Bpair=2000.
6970 IF Mfuel>2000. THEN Mfuel=2000.
6980 IF F>2000. THEN F=2000.
6990 IF Mhf>2000. THEN Mhf=2000.
7000 IF Mho>2000. THEN Mho=2000.
7010 IF Phf>2000. THEN Phf=2000.
7020 IF Pho>2000. THEN Pho=2000.
7030 IF Pc>2000. THEN Pc=2000.
7040 PRINT USING "DDD,3X,MD,DDDE ,3X,MD,DDDE ,3X,3(MD,DDDE ,3X
),3(MDD,DDDE ,3X),1X";J,Mair,Bpair,Mfuel,F,Mhf,Mho,Phf,Pho,Pc
7050 NEXT J

```

```

7060      PRINT ""
7070      PRINT USING "5A,5X,9(7A,7X)"; "Count", "Ta", "Tcin", "Tex1", "Tex2", "Tavgup
" "Tavgd1", "Tavgd2"
7080      FOR J=1 TO 10
7090          Volts=Temp(J,1)
7100          GOSUB Tcalc
7110          Ta=T
7120          Volts=Temp(J,2)
7130          GOSUB Tcalc
7140          Tcin=T
7150          Volts=Temp(J,3)
7160          GOSUB Tcalc
7170          Tex1=T
7180          Volts=Temp(J,4)
7190          GOSUB Tcalc
7200          Tex2=T
7210          Volts=Avgtemp(J,1)
7220          GOSUB Tcalc
7230          Tavgup=T
7240          Volts=Avgtemp(J,2)
7250          GOSUB Tcalc
7260          Tavgd1=T
7270          Volts=Avgtemp(J,3)
7280          GOSUB Tcalc
7290          Tavgd2=T
7300          IF Ta<100. THEN Ta=100.
7310          IF Tcin<100. THEN Tcin=100.
7320          IF Tex1<100. THEN Tex1=100.
7330          IF Tex2<100. THEN Tex2=100.
7340          IF Tavgup<100. THEN Tavgup=100.
7350          IF Tavgd1<100. THEN Tavgd1=100.
7360          IF Tavgd2<100. THEN Tavgd2=100.
7370          IF Ta>4000. THEN Ta=4000.
7380          IF Tcin>4000. THEN Tcin=4000.
7390          IF Tex1>4000. THEN Tex1=4000.
7400          IF Tex2>4000. THEN Tex2=4000.
7410          IF Tavgup>4000. THEN Tavgup=4000.
7420          IF Tavgd1>4000. THEN Tavgd1=4000.
7430          IF Tavgd2>4000. THEN Tavgd2=4000.
7440          PRINT USING "DDD,3X,7(MDD,DDE,4X)"; J,Ta,Tcin, Tex1, Tex2, Tavgup, Tavgd1, T
avgd2
7450      NEXT J
7460      GOTO Finish
7470 Finish:
7480      PRINTER IS 1
7490      PRINT USING "E"
7500      PRINT "DATA OUTPUT IS COMPLETE"
7510      DISP "SECURE TEST CELL !!!"
7520      BEEP
7530      PAUSE
7540      END

```

APPENDIX B

Run Checklist

TEST CELL # 1

1. Ensure yellow and top blue air valves in the solid fuel ramjet cell are closed.
2. Open lower blue valve (opens air line to Test Cell #2 or T-63).

** Note ** At least one valve should be open at all times from the main air line to ensure an air vent in the event of component failure.

NITROGEN BOTTLE ROOM

1. Fully open the control room nitrogen bottle. Ensure that there is at least 1000 psi.
2. Fully open actuator nitrogen bottle. Ensure that there is at least 500 psi available.

CONTROL ROOM

1. Ensure AC master switch is on and the red covered main air switch is closed on the solid fuel ramjet control panel.
2. Ensure the air flow set pressure is zero.
3. Ensure the T-63 combustion chamber safety thermocouple is installed and operating.

4. Ensure the fuel tank set pressure (gauge on panel) is less than 500 psi.

FUEL STORAGE ROOM

1. Open nitrogen bottle valve (need at least 400 psi more pressure available in the bottle than the desired fuel line/tank pressure, or 900 psi minimum).
2. Adjust hand loader to read 700 psi.
3. Slowly open the nitrogen gas supply valve located behind the fuel tank near the wall.
4. Slowly open the fuel line valve from the bottom of the tank.

OUTSIDE/CONTROL ROOM

1. Open main air plug valve to full open (minimum of 2500 psi required for a run).
2. Ensure all thermocouples are turned on (if required) and pressure transducers and tubing are secure at the test stand.
3. The heated sample line temperature control box should be set to 275 deg.F and the gas analyzers in the control room should be up and operating. The three main power switches for the electronic equipment racks should be ON.
4. Load and run the "T63NOX" computer program on the HP microcomputer. The pressure transducers should now be calibrated if not already done. Enter the appropriate zeros and constants in the program.

5. Set the main air pressure to 600 psi using the hand loader.
6. Set the fuel pressure to 500 psi using the hand loader.
7. Go through the flow rate set procedures in accordance with the computer program.
8. Ensure the printer is "on-line".
9. Check for personnel near the cell and for golfers. Activate the exterior warning horn and check main air flow rate when cued by the computer.
10. Check that safety key No. 3 is inserted and enabled.
11. Turn on the siren.
12. Start strip chart recorder and mark zero/ambient conditions.
13. Signal for start of purge nitrogen.
14. Activate main air ON.
15. Simultaneously, activate the toggled engine ignitor and fuel switch. Check desired fuel flow rate (0.33 GPM). Watch for hot or wet start by visually observing exhaust smoke at rig and monitor the digital combustion chamber safety temperature readout (commence shutdown if temperature reaches 1380 deg. F).
16. When steady-state operation is reached, begin traversing the Kiel probe in the augmentor tube and obtain analyzer measurements.
17. While at steady operation collect data with the HP microcomputer and from the gas analysis equipment.

18. After data is gathered, switch fuel OFF. Leave main air on until engine and augmentor tube are cool.
19. Turn main air OFF, record run time, and calculate fuel used during run. Update fuel board in fuel storage room.
20. Isolate fuel tank with valves and bleed excess fuel in lines with fuel switch activation.
21. Close main air valve outside.
22. Vent fuel tank from control panel if desired and close fuel tank nitrogen bottle.
23. Bleed remaining air heater and torch gases from lines and vent with remaining main air in lines. Back off pressure loaders to zero in the control room.
24. Secure analyzers, complete shutdown, and reduce data.

APPENDIX C

Gas Analyzer Checklist

Two Hours Prior

1. Turn on the Power to Model 900. It is not necessary to run any pumps at this time. When the heater has brought the unit up to temperature the temp cycle light will extinguish.

One Hour Prior

1. Turn on the Model 10AR power and ozone switch.
2. Turn on the Model 900 pump switch.
3. Plug in the vacuum pumps for the Model 10 and Model 900 (behind the cabinet on the floor).
4. Plug in the vacuum pump for the Model 900 mounted to the back of the unit.
5. Turn on the dilution gas to approximate one psi. This gas can be compressed ambient air.
6. Turn on O₂ for Model 10AR to 10 psi.
7. Expected readings on Model 900:

Chamber vacuum 23" Hg

Sample vacuum 10" Hg

Flow meter inside 1.8

Temp inside 175 deg F

Expected readings on Model 10:

Converter 650 deg C

Bypass 2.25 SCFH

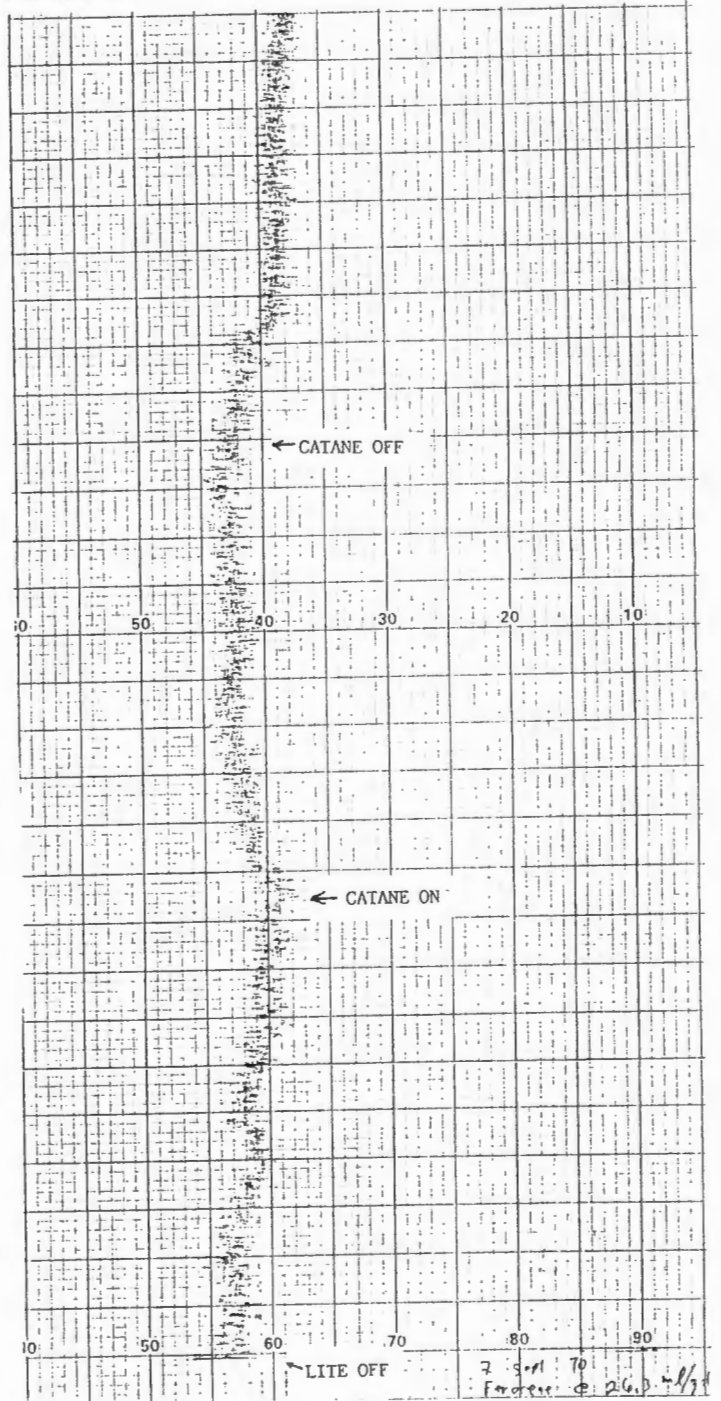
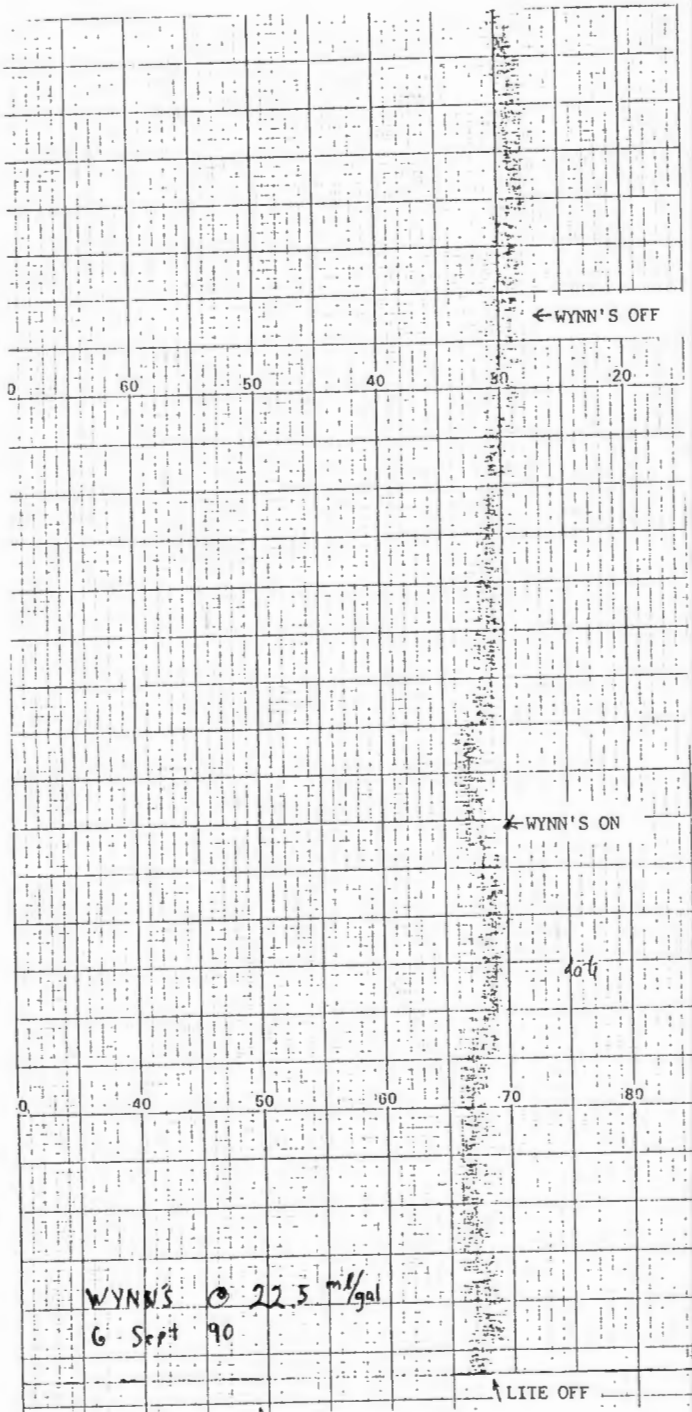
Sample	5" Hg
Reaction chamber	29.5"Hg
O ₂ press inside	2 psi

30 Minutes Prior

1. Turn on Model 48.
2. Turn on NO_x span gas to 3 psi an 0.8 SCFH and connect to span port of Model 900. Switch Model 900 to span. Note reading and adjust calibration to obtain exact concentration of span gas divided by 20.
3. Secure span gas and switch Model 900 back to sample and note Model 10 returns to zero.
4. Verify gas sample switch in test cell with air pressure.

APPENDIX D

Transmittance Data



APPENDIX E

TIMELINE FOR T-63 ADDITIVE TESTING

<u>Min:Sec</u>	<u>Event</u>
00:00	Purge air ON
00:02	Strip chart ON
00:05	Main air ON
00:07	Fuel ON
00:09	Ignitor ON
00:15	Engine light off (approx. 1200 F 0.33 GPM)
00:20	Check laser GO/NOGO Mark strip chart
00:25	Adjust view from IR camera if necessary
00:30	Operate at steady state no additive
01:00	Take hot run data HP and IR
01:45	Turn additive pumps ON
01:50	Mark strip chart
02:30	Take hot run data HP and IR
03:15	Turn additive pumps OFF
03:20	Mark strip chart
03:45	Take hot run data HP and IR
04:30	Secure fuel
04:35	Mark strip chart air only
04:55	Secure air
05:00	Secure purge/strip chart

LIST OF REFERENCES

1. Lefbevre, Arthur H., **Gas Turbine Combustion**, p.467, McGraw-Hill, 1983.
2. Lindsay, R.H., **An Experimental Investigation of Sooting Characteristics of a Gas Turbine Combustor and Augmentor Tube**, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1988.
3. Naval Postgraduate School, **Measurements of Gas Turbine Combustor and Engine Augmentor Tube Sooting Characteristics**, Young, M.F., Grafton, T.A., Conner, H., and Netzer, D.W., July 1988.
4. Cashdollar, K.L., Lee, C.K., and Singer, J.M., "Three Wavelength Light Transmission Techniques to Measure Smoke Particle Size and Concentration", **Applied Optics**, Vol. 18, No. 18, p. 1763-1769, June 1979.
5. USAF Engineering and Services Laboratory, **Soot Control by Additive-A Review**, by J.B Howard and W.J. Kausch, p.4, September 1979.
6. Glassman, I., **Combustion**, Second edition, p.329, Academic Press, 1987
7. Williamson, S.J., **Fundamentals of Air Pollution**, p. 279, Addison-Wesley Publishing Co., 1973.
8. USAF Engineering and Services Laboratory, **A New Catalyst For NO_x Control**, by B.W. Nelson, S.G. Nelson, M.O. Huggins, and P.A. Brandum, Sanitech Inc., June 1989.
9. Berry, L.G. and Mason, B., **Mineralogy; Concepts, Descriptions, Determinations**, p. 509-510, W.H. Freeman, 1959.
10. Kerr, G.T., "Synthetic Zeolites," **Scientific American**, v.262, p. 100-105, July 1989.
11. Grafton, T.A., **Measurements of Gas Turbine Combustor and Engine Augmentor Tube Sooting Characteristics**, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1987.

12. Behrens, C.K., **An Experimental Investigation Into NO_x Control of a Gas Turbine Combustor and Augmentor Tube Incorporating a Catalytic Reduction System**, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1990.
13. Headquarters, Department of the Army, **Technical Manual TM 55-2840-231-24, Organizational, DS, and GS, Maintenance Manual for Engine Assembly Model T-63-A-5A (2840-923-6023) and Model T-63-A-700 (2840-179-5536)**, p. 1-13, 3 March 1972.
14. **Instruction Manual, Model 900 Heated Sample Gas Dilution and Conditioning Unit**, Thermo Electron Corp., Hopkinson, Massachusetts, January 1983.
15. **Instruction Manual, Model 10A Rack-Mounted Chemiluminescent NO-NO_x Gas Analyzer**, Thermo Electron Corp., Franklin, Massachusetts, 1987.
16. **Instruction Manual, Model 48 GFC Ambient CO Analyzer**, Thermo Electron Corp., Franklin, Massachusetts, 1989.
17. Cruise, D.R. **Theoretical Computations of Equilibrium Compositions, Thermodynamic Properties, Performance Characteristics of Propellant Systems**, April 1979, Naval Weapons Center, China Lake, CA.
18. Kreith, Frank, **Principles of Heat Transfer**, p. 214-215, Intl. Textbook Co., 1959.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2.	Library, Code 52 Naval Postgraduate School Monterey, CA 93943-5002	2
3.	Department Chairman, Code AA Department of Aeronautics and Astronautics Naval Postgraduate School Monterey, CA 93943-5000	1
4.	Professor D.W. Netzer, Code AA/Nt Department of Aeronautics and Astronautics Naval Postgraduate School Monterey, CA 93943-5000	1
5.	Dr. Joseph Wander HQ AFESC/RDVS Tyndall AFB, FL 32403-6001	1
6.	Mr. Sid Nelson Sanitech Inc. 1935 E. Aurora Rd. Twinsburg, OH 44087	1
7.	Naval Air Propulsion Center Trenton, NJ 08628-0176 (Code: PE71:AFK)	1
8.	Naval Aviation Depot Alameda, CA 94501 (Attn: Roger Pesuit)	1
9.	Commanding Officer Naval Aviation Depot Pensacola, FL 32508-5300	1
10.	LCDR K.R. Engel 2690 Mathis DR. Marianna, FL 32446	2

- | | | |
|-----|--|---|
| 11. | Naval Weapons Center | 1 |
| | China Lake, CA 93555 | |
| | (Code 3246 W. Burdette) | |
| 12. | Prof. R.P. Shreeve, Code AA/Sf | 1 |
| | Department of Aeronautics and Astronautics | |
| | Naval Postgraduate School | |
| | Monterey, CA 93943-5000 | |

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93943-5002

DUDLEY KNOX LIBRARY



3 2768 00005180 9